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# PHYSICAL OPTICS,

OR,

# THE NATURE AND PROPERTIES OF LIGHT:

## A DESCRIPTIVE AND EXPERIMENTAL TREATISE.

BY

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UPPER GOWER STREET, AND IVY LANE, PATERNOSTER ROW.
1856.

115. a. 5.

He feels that he has no need to apologize to the scientific world for describing the most homely contrivances for experiments, knowing that, with simple and inexpensive apparatus, the most important discoveries have been made, and will continue to be made, in this science.

An ignorant man may smile equally upon the child blowing soap-bubbles for amusement, and upon the grave, thoughtful philosopher contemplating the fine colours they exhibit when very thin, and thinking of the explanation of them. The philosopher will continue nevertheless seriously to contemplate the soap-bubble, conscious that he comprehends what he sees; which is beyond the feeble intelligence of the uneducated. The beautiful and often gorgeous phenomena which are continually presented to the observer in the experiments of this science, call forth exclamations of surprise from even the most ignorant; and the question, how does this happen? is made with anxious countenance by those who are not prepared to understand the only answer which can be given to their own question. The author hopes that this question is answered in the present treatise, and in a manner comprehensible to all who have sufficient patience for the study, without entering into mathematical details.

He hopes that the mathematical student will find the present work an introduction to the science, which will enable him to examine for himself the experiments, and see their bearing upon the received theories. In another volume he will discuss mathematically the results described in the present treatise.

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## ERRATA.

Page 37, line 22, *for* latter *read* former.
„ „ 23, „ former „ latter.

# PHYSICAL OPTICS:

## THE SCIENCE
## OF
## THE NATURAL PROPERTIES OF LIGHT.

## INTRODUCTION.

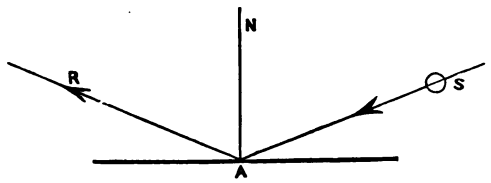
WHEN we first endeavour to form an opinion as to *what light is,* we recur to the opposite, darkness, or privation of light, and see that light must arise from some luminous origin or shining surface, either directly or indirectly. But considering light to originate in some self-luminous surface, we recollect that there are many which give out light; such as flames of different kinds, incandescent substances, as burning charcoal, metals, and earths at high temperatures, phosphorescent substances at low temperatures, the glow-worm and many insects from animal life, the electric light, &c., besides the heavenly bodies whose existence is only known to us by the light they give out. With such variety of origins we might well despair of forming any conclusive opinion upon the nature of light; as we ascend however from the more evident properties which it presents, to others which are less so, and from these again to others which are more and more intimately connected with its essential constitution, we arrive at the means of judging of its nature, in a far higher degree than can be appreciated by those who have not followed that course of examination. We are thus led to form hypotheses of the nature of light in order to explain the phenomena it presents; these hypotheses ought not to be accepted, however, longer than they suffice to that end.

We call a shining surface self-luminous when the light originates there; but the light from it falling on the surfaces of bodies renders them visible also; visibility meaning the property of being perceived by the eye. In this manner opaque bodies acquire a property similar to luminous origins, and it is thus that the planets shining by the light they receive from the sun, are only distinguished from the fixed stars by their motion in the heavens, or by their exhibiting determinate discs when seen in telescopes. Here we meet with the property of the reflexion of light. It is sometimes regular, as when the light falls on a polished surface, like that of water or mercury, the facets of many crystals, polished mirrors, &c.; but in others and the more common cases it is irregular, as when it falls on the rough surfaces of bodies. These latter are visible by the eye in a great variety of positions, by means of this irregularly reflected or dispersed light coming from them; the former only when the eye is so situated as to receive the regularly reflected light, supposing them to furnish no dispersed light, which, however, is never absolutely the case.

When light has been reflected, it has generally received new properties, and in some cases it is entirely polarized; on the other hand, if polarized before reflexion at a surface, the dispersed light is found to have lost its property of polarization, and to have become depolarized by reflexion.

The law of the reflexion of light at polished surfaces is so simple, that it has been known from ancient times. When an elastic ball is thrown against a hard surface, it rebounds from the surface at an angle nearly equal to that with which it impinged; the perpendicular drawn to the surface at the point of impinging, the original direction of the ball and its direction after rebounding lying all in the same plane. If the ball were perfectly elastic, the angles would be

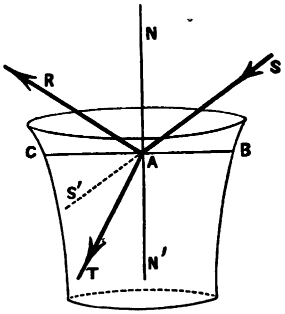
Fig. 1.



exactly equal. In the figure, let SA be the direction of motion of the ball before striking the hard plane at A, and let AR be the direction in which it rebounds, draw also AN a perpendicular to the hard surface at A. Then the angles SAN and NAR are in the same plane, and the angle SAN equals the angle NAR. It is found that the same law holds with respect to the reflexion of light.

*Definition* 1. A *ray* of light is the smallest portion of a beam of light which we can imagine to exist separately, and it is represented by a straight line SA, which is its direction whilst in the same medium. In the same way the line AR represents the *reflected ray* corresponding to the *ray* SA, which is called the incident ray. When CAB (fig. 2) is the surface of a transparent medium such as water, a portion of the light enters the medium and is turned out of the original course SAS′ towards the perpendicular line NAN′; this breaking of its course into a new direction AT, is called the refraction of light. The line AT represents the refracted ray.

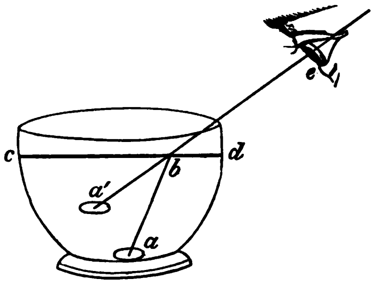
Fig. 2.



*Def.* 2. The angle SAN is called the *angle of incidence*.
*Def.* 3. „ NAR „ *angle of reflexion*.
*Def.* 4. „ TAN′ „ *angle of refraction*.

That a ray of light is *refracted* on passing from one medium to another of a different density, is shown by an easy experiment. Attach a coin with wax to the bottom of a cup as at *a* in fig. 3, place the eye at such a position *e* that the coin is hidden by the edge of the cup; if now an assistant pours water into the cup to some height *c d*, the coin will appear over the edge as at *a′*, and the visual rays must have followed the broken course *abe* to reach the eye; the refraction at *b* on

Fig. 3.

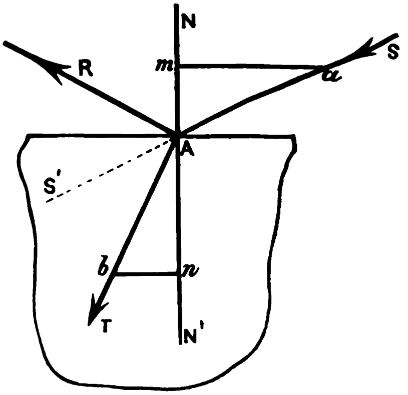


passing from *water* into *air* being *from* the perpendicular to the surface. It is found that the course of a ray would be the same whichever way it passed, that is, a ray would pass from *e* to *a* along the path *eba*.

It was only in late times that the law of the refraction of light was discovered by Snellius*, as follows.

In figure 4, SA, AR, AT representing the incident, the reflected and the refracted rays respectively as in fig. 2, measure off a distance A*a* on the incident ray SA, and an equal distance A*b* on the refracted ray AT; draw perpendiculars *am*, *bn* on the perpendicular line to the surface NAN′; then the ratio which *ma* bears to *bn* is the same whether the angles SAN, TAN′ be great or small; or otherwise the fraction $\frac{ma}{bn}$ is constantly of the same value for all angles of incidence and refraction. This, with the condition that the angles SAN and TAN′ are in the same plane, is called the *law of the sines* when we use trigonometry, or the law of Snellius. If we put the Greek letter $\mu$ for the constant value of the above ratio, we have $\frac{ma}{bn}$ equal to $\mu$, which indicating by its value the degree of refraction, we call it the *index of refraction*.

Fig. 4.



Now as the refracting medium becomes more dense, the value of $\mu$ or $\frac{ma}{bn}$ becomes greater. It is about $\frac{4}{3}$ when light passes from air into water, about $\frac{3}{2}$ when it passes from air into glass, and about $\frac{5}{2}$ when it passes from air into diamond. Inflammable substances, however, refract more in proportion to their density than others, which led Newton to believe what has since been proved, that the diamond was inflammable.

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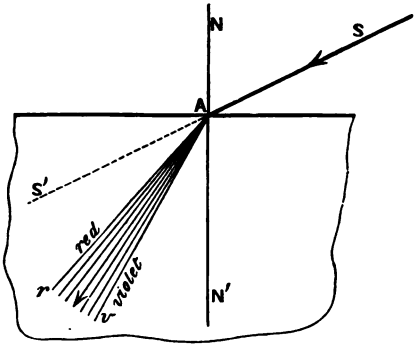
* Huygens' 'Opera Reliqua,' vol. ii. page 2.

The law of the reflexion of light is thus enunciated. *The incident ray, the reflected ray, and the perpendicular to the reflecting surface at the point of incidence, lie all in the same plane; and the angle of reflexion equals the angle of incidence.*

The law of the refraction of light is thus stated. *The incident ray, the refracted ray, and the perpendicular to the refracting surface at the point of incidence, lie all in the same plane; and the sine of the angle of incidence bears a constant ratio* $\left(\frac{ma}{nb}\right)$ *to the sine of the angle of refraction.*

Sir Isaac Newton's great optical discovery was this,—that white light consists of all the colours of the solar spectrum; and that they are only *separated* from the other colours when we see them, and are not white light (considered simple light) which has been changed to coloured light by some means. He found that the differently coloured rays are differently refracted*, red being the least, violet the most refracted, and the refraction increasing from the red rays, through orange, yellow, green, blue, indigo to the violet rays. From this property, a ray of white light which is made up of all shades of colour is spread into a fan-like form when it enters a refracting medium obliquely. In figure 5 this is shown by taking SAS′ for the original direction of the ray, and the angle S′A$r$ the deviation for the red, the angle S′A$v$ that for the violet ray. This constitutes the *chromatic* or coloured *dispersion* of light.

Fig. 5.



When we say that white light consists of all shades passing through red, orange, yellow, green, blue, indigo to violet, it is not meant to say that the solar spectrum shows a continuous shading of tints through these colours. About the year 1814, M. Fraunhofer, using the fine prisms of the manufactory at Munich, with which he was connected, discovered that the pure solar spectrum contains numerous black lines across it which are the places of deficient tints. The figure below, copied of one-fourth the size of M. Fraunhofer's* engraving, will serve to show the places of some of these *fixed lines of the solar spectrum* of Fraunhofer.

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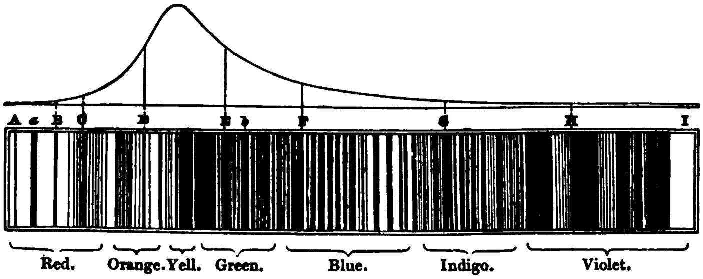
* Newton's 'Opticks,' Prop. I. Theor. 1.—"Lights which differ in colour, differ also in degrees of refrangibility."



A triangular chandelier drop, which can be purchased at a small price at many glass shops, will serve for an optical prism for common use, to form a solar spectrum, by allowing the sun's light to shine through it upon a distant sheet of white paper; or to look through when we want to analyse lights, colours, and dyes; but to see Fraunhofer's fixed lines we must have a good prism. When the prisms of pure glass, with flat and accurately polished sides, are not at hand, a hollow prism formed with pieces of well and flatly polished plate glass, cemented together with japanners' gold size (which can be purchased at the artists' colour shops), and filled with water or alcohol, may be well employed. The prism need not be more than a cubic inch in bulk, and should be used in Fraunhofer's manner, by placing it on a support attached on the object end of a small telescope.

In fig. 6, E being the eye end, and *o* the object end of a small telescope, let ABC be a support of wood, which will slide on the end *o*, and *abc* the prism, attached with wax or otherwise to the support; a line of light, as *de*, is to be looked at through the telescope and prism, when the chromatic spectrum will be seen in the field of view.

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* Denkschriften der Akademie zu München, 1814, 1815.

The precautions requiring to be attended to, in order to have the spectrum *pure,* and the fixed lines *distinct,* are these: first, the line of light *de* must be narrow, such as light thrown through a slit between two knife-edges which are set parallel, and $\frac{1}{50}$th to $\frac{1}{100}$th of an inch apart, and *it must be parallel* to the refracting edge of the prism; secondly, the prism must be set so that the light makes the *same angle* with the first surface of the prism, when it falls upon it, as it does with the second surface when it leaves it, or in figure 7 the angle of incidence at A must equal the angle of emergence at B. The angle of deviation C*a*D is about half the angle of the prism for glass, and about one-third of it for water, when the angle of the prism is not large. When sunlight is examined, it will be necessary to have a mirror to throw the light into a darkened room through an opening in a window-shutter, and the telescope should be as distant as possible, being set to the focus to show the line of light distinctly, before the prism is set in its place; and after that is done, the telescope and prism must be turned round to the requisite angle of deviation, so that the beam on emergence from the prism may pass up the tube of the telescope. When artificial lights are examined they must be placed behind the narrow slit, and the fixed lines will be found

Fig. 6.

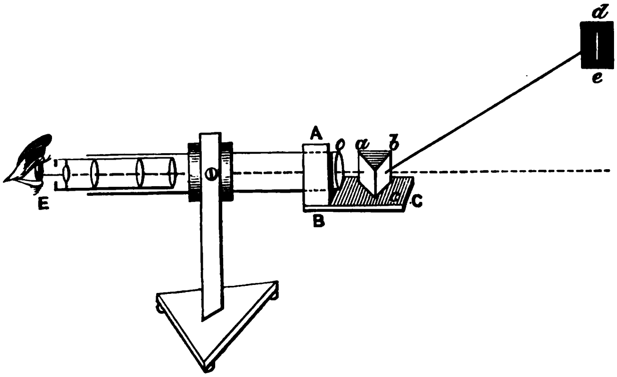
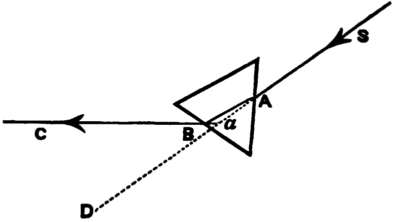


Fig. 7.

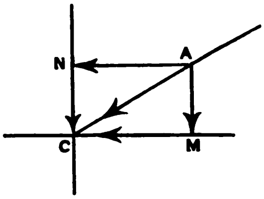


to differ very greatly from those in sunlight, and from each other. The double line D, where light is wanting in sunlight, is the brightest part in oil-flames, and it is the entire light when a spirit-lamp (alcohol) has a little common salt put on the wick. This last-named lamp is the one used in delicate optical experiments where it is necessary to have a *homogeneous* light, or light of one tint only.

When we come to consider how the laws of reflexion and refraction of light may arise physically, it is convenient to consider the motion of a ray as made up of two motions, one parallel, and the other perpendicular to the surface on which the light is incident.

When a body moves with a certain velocity in a direction AC (fig. 8), if we take the length AC to represent the velocity, then it is shown in mechanical treatises that the same velocity would have arisen if two velocities represented by AN and AM, the sides of the parallelogram of which AC is the diagonal, had been simultaneously given to the body. Then the two velocities are said to be compounded into one. The reciprocal of this is also true, that a velocity in any direction may be considered decomposed into two others represented by the sides of a parallelogram, of which the diagonal represents the given velocity. The sides of the parallelogram may be at right angles, or at any other angle to each other.

Fig. 8.

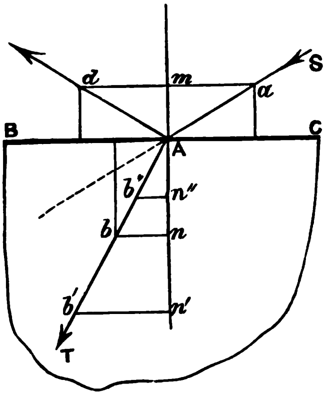


Applying this parallelogram of velocities to rays of light, we see that the motion of the ray *parallel* to the reflecting surface is not changed in reflexion, but that the motion *perpendicular* to the surface is reversed, the ray being thrown back perpendicularly with the velocity with which it was perpendicularly incident, that is, supposing the reflected ray to move with the velocity of the incident ray.

For measuring off the distances A*a*, A*d*, and A*b* (fig. 9) equal to each other, then describe parallelograms with these lines for diagonals, and with their sides parallel and perpendicular to the surface BAC, we shall have the parallel velocities *am* and *md* equal, and the perpendicular velocity *m*A of the incident ray equal, but opposite to the perpendicular velocity A*m* of the reflected ray.

If we suppose the parallel velocity in the refracted ray to be unchanged as it is in the reflected ray, we must find a point *b*′ in AT, such that *b*′*n*′ equals *am* or *md*, and then the perpendicular velocity A*n*′ must be greater than A*m*, and the whole velocity represented by A*b*′ must be increased also. Now this would imply an attraction perpendicular to the refracting surface, for the refracted ray increasing its velocity, and a repulsion throwing back the reflected ray, but leaving its velocity in its own direction, the same as in the incident ray.

Fig. 9.



Newton and other philosophers have supposed light to move quicker* in dense media than in a vacuum from a perpendicular attractive force. Huygens had, however, previously supposed the velocity to be slower† in dense media. Some of Newton's experiments enabled Dr. Young‡ to show that light really moves slower in dense refracting media according to Huygens's view; and this has been confirmed by very different experiments made by M. Fresnel§ and the author‖. Huygens's supposition was this, that the velocity of light in a vacuum was to the velocity in the refracting medium as the line *am* to the line *bn* (fig. 4); and also in fig. 9 if we take A*b* equal to A*a*. Then the velocities have the ratio $\frac{am}{bn}$, which is the refractive index $\mu$, and constant. Take in fig. 9 a point *b*″, such that the ratio $\frac{\mathrm{A}b}{\mathrm{A}b''}$ equals $\mu$, the refracted light will have traversed the space A*b*″, whilst the reflected light has passed over the space A$d$. From this foundation Huygens showed that the law of the sines must arise as a natural consequence, provided light arises from waves in an æthereal medium, in the same manner as sound arises from waves in the air; and that a wave may be considered as formed by a series of small waves, into which the original light was broken in falling upon the refracting surface. This was the first proposal of the undulatory theory of light. DesCartes had previously proposed a vibratory theory, but had not advanced to an undulatory theory. Dr. Hooke, in his 'Micrographia,' not only adopts an undulatory theory, but first advances the *doctrine of interference* in light. In order that these vibrations and undulations or waves may exist, it is required that there should be an elastic medium suitable for their transmission; and it has been generally called the *luminiferous æther*. It is supposed to pervade all space, and to be either of different density or of different elasticity within dense bodies to what it is without them, so as to travel through them with diminished velocity.

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* Newton's 'Opticks,' pp. 69 and 245.

† Huygens's 'Traité de la Lumière,' p. 34.

‡ Philosophical Transactions for 1802.

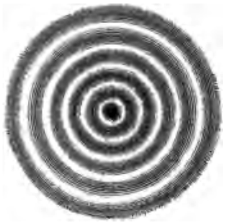
§ Annales de Chimie et de Physique for 1815, vol. i. p. 239.

‖ Philosophical Magazine for 1833, vol. iii. p. 333.

A similar supposition of the original wave being broken into small waves at the surface of the dense medium, enabled Huygens to explain the *reflexion* of light, on the undulatory theory.

We shall find further on, that this undulatory theory of light cannot be the true theory, yet it has led to the discovery of some of the most important properties of light; and the student should understand its nature and results. Suppose a stone thrown into still water at a place such as the center of the fig. 10, there will arise a series of circular waves around this point, the water rising and falling successively at the center and other points of the surface; and the waves spread in circles outwards, but become less and less deep as they are further from the center. Each point on the surface of the water has thus a vibratory motion ascending and descending, and so gives rise to an undulatory or wave motion upon the surface. The waves diverging from the center, spread at right angles to the nearly upward and downward motion of the vibrations. These latter are from this called transversal vibrations.

Fig. 10.



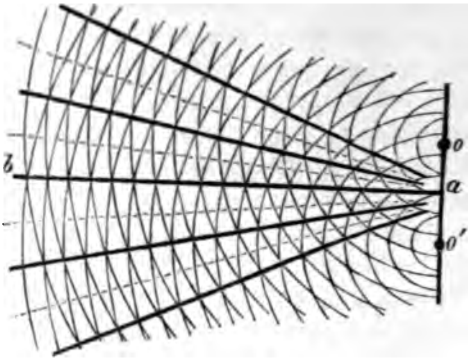
In the undulatory theory of light, *the direction* in which a wave within the hypothetical æther comes to any point is direct from the center or luminous origin, and corresponds to what is termed a ray of light; therefore in general, though not always, the ray direction is the perpendicular to the wave.

There is an essential difference between the waves supposed to constitute light and those forming sound in air; both must have an origin as center *within an elastic medium,* but sound arises from vibrations in the air *in the direction* in which the sound wave travels, and not at right angles or transverse to it, as the phenomena of light require. We can easily see that the vibrations forming sound must be longitudinal, or *in the direction* of the sound ray, from what takes place as a bell is struck, the side of the bell communicating its vibrations to the air in the direction in which the sound travels.

The undulatory theory contains within itself the property of *periodicity* essentially, because the waves arise from the vibrations of the particles of the æther, and these take place in regular periods, as a pendulum swings in regular oscillations. Now the oscillations occupy, when they are small, the same *time* or period, whatever their magnitude with respect to each other, and so in waves at the surface of water they are less and less deep as they are further from the center, yet the vibrations of the particles on the surface of the water take place in the same time near the center as at a distance from it, and the waves also travel outwards with the same velocity, and maintain the same distance from each other nearly.

The property of *periodicity,* or as we may call it the regular recurrence of phenomena, explains the beats heard when two musical notes are sounded together, and the jars of discords on the ear, which evidently arise from the sound waves interfering with each other. It is easy to see how two series of waves at the surface of water must interfere with each other where they meet. If the water ought to rise at a given place from one set of waves, and fall from another set an equal height, the two tendencies being equal and opposite must destroy one another, and leave the surface level. If *each* would cause the water to rise or fall at any point, the conjoint effect would be to make it rise to a greater height, or fall to a greater depth. Intermediate tendencies would produce intermediate effects, but still there would be interference; so that when two sets of waves exist at the same places and times, the results everywhere are *interference results*, the two sets of waves passing through each other at the same time.

Fig. 11.



These can be easily seen by throwing two stones simultaneously into a pond of still water, as at the points *o* and *o′* in the figure, and then the waves originating simultaneously around each origin, the interference is regular. If we draw a line *oo′* from *o* to *o′*, and draw *ab* bisecting it perpendicularly, the interference is evidently symmetrical on each side of this line *ab*, and as each point in the line *ab* is at an equal distance from *o* and *o′*, the waves arrive in the same state of vibration, and therefore strengthen each other. At some distance on each side of *ab*, the waves arrive in *opposite* states of vibration, and then destroy each other, as along the dotted lines. At a further distance again they strengthen each other, as along the continuous curved lines outside the dotted ones, and so onwards for many alternations. Now these are readily seen on the surface of water, and form the best illustration of what occurs in sound.

An undulatory theory of light therefore involves interference of light, two lights coming together sometimes strengthening each other, and producing a brighter light, and sometimes destroying each other and producing darkness; and Dr. Hooke, Dr. Young, and M. Fresnel, adopting that theory, explained the occurrence of periodically recurring colours by the doctrine of interferences. By their investigations, but especially by those of M. Fresnel, who brought high mathematical talents to bear upon the subject, the property of interference in light must now be considered as demonstrated, although the undulatory theory by which it was discovered will have to be abandoned; since the interference along the line *ab* turns out to be *dark,* and not *bright* interference, which it should be by the undulatory theory, when the experiment is tried in correct circumstances.

The occurrence of darkness where brightness should take place, and the converse of brightness where darkness should be, shows that the *mechanical* undulatory theory cannot be true. Our alternative is to study light upon *chemical,* and not simply *mechanical,* principles, with luminiferous surfaces following each other at regular intervals so as to interfere.

We shall be better able to examine the results of the interference of light when the phenomena of double refraction and polarization have been discussed; since many of the most interesting and important cases are connected with those properties.

# CHAPTER I.

## ON DOUBLE REFRACTION.

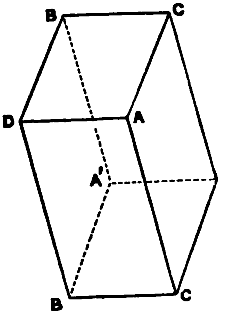
The law of the ordinary refraction of light discovered by Snellius, or the law of the sines, applies to uncrystallized bodies generally, such as water, glass, air, gums, &c., and to many crystals, amongst which are common salt, alum, and fluor-spar; but there are numerous crystallized bodies which have double refraction, such as nitre, calcareous spar, called also Iceland spar and rhomboidal carbonate of lime, ice, topaz, mica, selenite or crystallized plaster of Paris, quartz crystal, chromate of potash, and many others. In these latter, a ray of common light is refracted into two rays within the crystal.

The double refracting crystals are divisible again into two classes, one called uniaxal crystals, the other biaxal crystals. The uniaxal crystals refract one of the rays according to the ordinary law of the sines, and the other according to an extraordinary law. In the biaxal crystals both the refracted rays have extraordinary refraction.

The uniaxal crystal, calcareous spar (more commonly called calc spar), is found in abundance in many lead mines, but the purest specimens are brought from Iceland. It has powerful double refraction, is generally colourless and transparent, and can be highly polished, so that some of the most valuable apparatus for studying Physical Optics are formed of it. It cleaves easily in certain directions, by a blow on the back of a knife when the edge is laid along these directions. These cleavage planes produce rhombic faces which have always the same angles. The more recent measures of these angles will be found in treatises on mineralogy, but Huygens's measures will be here retained.

If we take fig. 12 to represent a portion of crystal, we find the rhombic faces, as ACBD, to have obtuse angles at A and B equal to 101° 52′, and acute angles at C and D equal to 78° 8′. The solid angle at A is formed by three obtuse angles of the rhombs, and the same at the opposite solid angle $A'$; each of the other solid angles is formed by one obtuse and two acute angles of the rhombs.

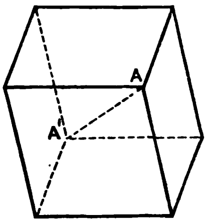
Fig. 12.



Placing one of these crystals over any object, such as a letter in the printed page of a book, on looking through the opposite face the object appears double, or the rhomb gives double images.

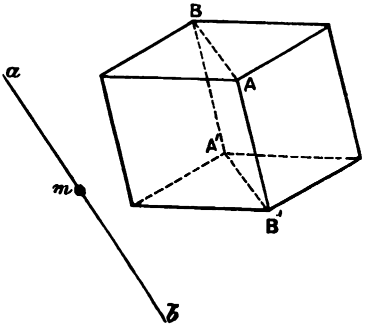
If we take a piece of crystal and cleave out of it a rhomb with each of its edges of the same length, as in fig. 13, with A and $A'$ the obtuse summits formed each of three obtuse angles, then the line joining A and $A'$ is the axis of the crystal, and is equally inclined to each of the three faces of the crystal which meet at A and at $A'$. Now the refraction was found by Huygens to be symmetrical around this line $AA'$, and hence it is correctly called the optic axis of the crystal. As innumerable small pieces may be made from a given piece of crystal to fulfil the above conditions, it is clear that the optic axes in a crystal are innumerable, but all parallel to a given direction.

Fig. 13.



If we take the equal-edged rhomb, and, as in the next figure (14), were to draw lines joining the opposite angles A and B, $A'$ and $B'$, they would bisect the obtuse angles.

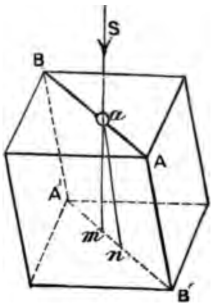
Fig. 14.



Draw on a piece of paper a long straight line *ab*, making a spot *m* upon it, and place the crystal over it so that the points $A'$ and $B'$ are both over some part of the line *ab*; now looking through the upper face of the rhomb, if the eye is anywhere in the plane passing through AB A'B' which is perpendicular to that face, the images of the spot *m* upon *ab* are seen both in the same line with the parts of it beyond the crystal. If the eye is on either side of that plane, the two images of the spot are seen to separate from each other, and from the part of *ab* outside the crystal, the separation being symmetrical on each side of that plane. If we place the crystal with the line joining A'B' inclined to *ab*, we see the two images both to be out of the direction *ab* wherever the eye is placed, except when directly over the surface, when one image is in that direction. The refraction being symmetrical with respect to the plane AB A'B', it is called a principal plane of the crystal. If we had used either of the other equal faces of the rhomb which meet at A, we should have found the same results for the planes found like AB A'B', and the line joining A and A' is the common intersection of these three principal planes, and is hence the optic axis of the crystal.

If we cover one face of the rhomb with paper, or better with tinfoil, having a small hole in it, say in the line AB, such as *a* in fig. 15, and pass a ray of light S*a* through it, then if S*a* be perpendicular to the face of the rhomb, one refracted ray, as *am*, enters the crystal without deviation, or S*am* is a straight line, and the other is refracted into the line *an* in the principal plane, the angle *m a n* being about 6° 40'. When the ray S*a* is inclined *in the principal plane*, so that the angle B*a*S is 73° 20', the line S*an* is a straight line. It is clear that *am* is the ordinary refracted ray, and the ray *an* the extraordinarily refracted ray.

Fig. 15.



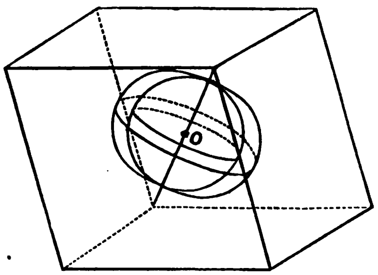
Similar experiments may be more easily made by placing as above an ink spot *m*, with a long straight line drawn through it, on paper under the rhomb, and examining the position of the images by the eye situated over the rhomb; remembering that as an ordinary ray from *m* and extraordinary ray from *n* would pass through the small hole *a* both in the line S*a*, therefore if the eye is placed in the line S*am* and looks towards a spot at *m*, the extraordinary ray now coming from *m*, where the upper surface is uncovered, would be seen to emerge nearer to B, since whilst within the crystal it was parallel to *an*, the eye being supposed distant.

By various other experiments and taking measures of the distances observed, Huygens found one ray to be an ordinary and the other an extraordinary ray. The refraction of the ordinary ray had the same properties, and yielded the same appearances as a ray in uncrystallized substances, that is, the refractive index was constant and equal to $\frac{5}{3}$ nearly, which is about the same as in some kinds of flint-glass. On the other hand, the refraction of the extraordinary ray gave a refractive index which was variable, being $\frac{5}{3}$ nearly, along the axis AA′ and $\frac{40}{27}$ or $\frac{8}{9}$ of $\frac{5}{3}$, in the direction perpendicular to AA′. M. Malus, in his treatise 'Théorie de la Double Réfraction,' page 199, gives the values of the greatest and least refractive indices from very accurate measures as 1.6543 and 1.4833.

Having adopted the undulatory theory of light, according to which light radiates around a luminous point in an ordinary medium by spherical waves, Huygens tried the result of a spheroidal wave, formed by the revolution of an ellipse about its minor axis, for the extraordinary rays in calc-spar, and found that the phenomena were perfectly represented by it, which has been confirmed by several other observers.

Suppose *o* to be a luminous point within the crystal from which light emanates in all directions, draw through *o* the optic axis, which we suppose to be the line AA′ of former figures, and taking any distance from *o* as a radius, describe a spherical surface, as in fig. 16, this may be taken to represent a luminiferous wave of ordinary light in some one of its positions. Take the diameter of the sphere in the optic axis for the minor axis of an ellipse, and with center *o* and a major axis $\frac{9}{8}$ths of this minor axis describe

Fig. 16.



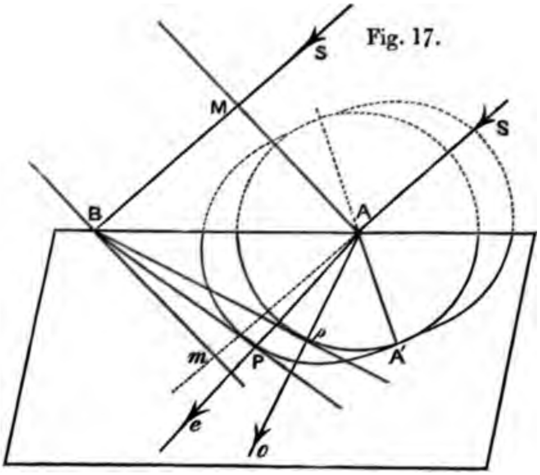
an ellipse; then the revolution of this ellipse about the optic axis will generate the spheroidal surface, which is the luminiferous wave of the extraordinary refraction corresponding to the spherical one of the ordinary refraction.

Now although we cannot cause light to originate in this manner within a crystal, yet we can form a luminous point in several ways *upon* one of the faces of the crystal, for instance, the luminous point formed when a lens of one-inch focus is held in the sun's light, which is a minute image of the sun of less than $\frac{1}{100}$th of an inch diameter, may be thrown upon the face of the crystal, and also the light of day passing through a minute aperture in tinfoil upon the surface may be used. In these cases the light emanates from the luminous point in a spherical and a spheroidal surface within the crystal, their common axis being parallel to the optic axis of the crystal.

Huygens has shown that if a *plane* wave were incident on a uniaxal crystal, the two refracted waves would be each plane waves, and be found by the following rule.

Suppose two rays, SA, SB, coming from a very distant luminous point so that they are considered parallel, and the wave to which they are perpendiculars is a plane wave in each position as it moves along. Let AM be the section of the wave when it arrives at A, and B*m* that which would have been the section when it arrived at B if the crystal had not intervened, A and B

Fig. 17.



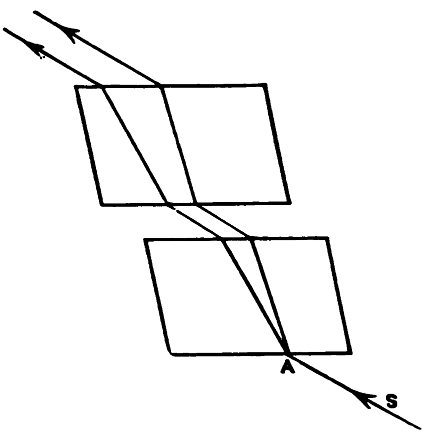
being in the surface of the crystal. Let AA′ be parallel to the optic axis, which may be inclined to the plane of the figure; take AA′ a distance having to A*m* a constant ratio, and such that $\frac{Am}{AA'}$ is the refractive index for the ordinary ray, and with center A and radius AA′ describe a spherical surface; then drawing a plane B*p* touching the sphere at *p*, and a line A*po* through A and *p*, the plane B*p* is the ordinary wave when the point M has arrived at B, and A*po* is the ordinary ray corresponding to SA without the crystal.

Again, describe a spheroid with center A, semi-minor axis AA′, and a semi-major axis, as in the figure, $\frac{9}{8}$ of AA′, and draw a plane BP touching it in P, which will generally be out of the plane of the paper, and it will represent the extraordinary wave; also drawing the line AP*e*, this will represent the extraordinary ray.

The rays were perpendicular to the wave-surface in air before incidence, and A*po* is so also in the crystal, but A*pe* is not generally a perpendicular to the extraordinary wave in the crystal. When the rays emerge from the opposite parallel face of the crystal into air again, the converse refractions take place, and the emergent rays are each parallel to the incident ray SA, and become again perpendiculars to the emergent waves.

When two rhomboids are placed one over the other, as in fig. 18, with their corresponding faces parallel and similarly situated, they act as a single rhomb, whose thickness is the sum of their thicknesses, causing a further divergence of the rays, as in the figure; the incident ray SA giving two rays in the first crystal, and the emergent rays between the crystals being parallel to SA. Then falling on the surface of the similarly situated second rhomb, the ordinary ray gives another

Fig. 18.



ordinary ray, parallel to its course in the first crystal; and the extraordinary ray gives similarly another extraordinary ray in the second crystal, parallel to its direction in the first; both finally emerge parallel to SA from the second surface of the second crystal.

When the *principal plane* of the *second* crystal is set at *right angles* to that of the first, we have again only two finally emergent rays, but the ray which was the ordinary ray in the first crystal, furnishes the extraordinary ray in the second, and, in like manner, the extraordinary ray in the first crystal becomes the ordinary ray in the second. If the two crystals are placed with their principal planes in *any other* relative positions, *each* of the two rays is divided again into two within the second crystal, and furnish *four* finally emergent rays.

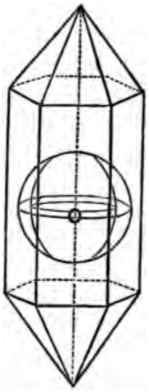
The undulatory theory as first imagined by Huygens offered no solution to these phenomena, but Newton having adopted a mixed corpuscular and vibratory theory, on considering the same subject, although he overlooked Huygens's correct law of the refractions, and gave an inaccurate one of his own, yet saw that the luminiferous corpuscles of his theory might have different properties on different sides; and hence according as the sides of the rays were presented to the sides of the crystals, arose the peculiar actions of the crystals upon them. As a means of fixing the ideas, we may compare the luminiferous corpuscles with minute magnets, having each a north and a south pole, and hence the term polarization of light, which is also now retained in the undulatory theory. The explanation of the various phenomena of polarization will be found in the next Chapter, and it is here only necessary to state that the two rays into which a ray of common light is refracted are polarized in planes at right angles to each other, in double refracting crystals.

When common light is incident on the crystal the two rays are of equal brightness, but if the incident light is polarized their intensities are generally different. For this reason, when the single incident ray SA has become four emergent rays from the second crystal, they are unequal in brightness in pairs, of which the law is easily traced.

We have seen in calc-spar that the ordinary luminiferous surface was found to move slower than the extraordinary one, except along the optic axis. Generally the velocity *in air* having to the velocity *in the medium* the ratio which is the refractive index, the velocity in the medium is *less* as the refractive index is *greater*; and hence the variable refractive index of the extraordinary ray is *less* than the constant refractive index of the ordinary, except along the optic axis. For this reason calc-spar and other crystals have been called negative crystals.

There are other crystals in which the ordinary ray travels quicker than the extraordinary ray, and these have been called positive crystals. Quartz and ice are considered to belong to this class, but quartz has peculiarities which will be found noticed in the Chapter on Interference. In quartz, the optic axis is the axis of the six-sided prism, in which it is frequently found with pyramidal terminations. Supposing *o* in fig. 19 to be a luminous origin, let the sphere represent again the luminiferous surface of the ordinary rays, then that of the extraordinary rays will be a *prolate* spheroid formed by the revolution of an ellipse about its *major* axis. The reader will find tables of double refracting crystals in Sir David Brewster's treatise on Optics.

Fig. 19.



It has been determined from certain interference experiments that the spheroid is of different ellipticity for different colours in some substances, and in *leucocyclite* and *vesuvian** produces remarkable results.

When the magnificent interference phenomena seen in polarized light near the optic axes of crystals, were found by Arago, Biot, and Brewster to present great variety, some exhibiting circular rings round one axis, and others ovals and lemniscate curves round two axes, it became evident that Huygens's law applied only to certain crystals which we now call *uniaxal*.

Dr. Brewster, in 1818, having shown that the refraction in biaxal crystals required the introduction of new considerations, he maintained that the optic axes are resultant or compensation axes only†, arising from the "opposite action of *two* or more rectangular axes, the principal one of which is the line bisecting the angle formed by the two resultant axes."

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* See Herschel's treatise on Light in the 'Encyclopædia Metropolitana,' article 1125.

† See Brewster's 'Optics,' p. 207, ed. 1831, and p. 266, edition of 1853.

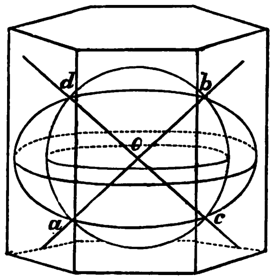
The doctrine of *transversal* vibrations in the undulatory theory of light having been adopted by Dr. Young and M. Fresnel, in order to explain the phenomena of the polarization of light, the latter, in his "Mémoire sur la double réfraction*," has shown the form of the wave-surface in biaxal crystals, which would arise from the elasticity of the hypothetical æther within the crystal being referred to three principal directions at right angles to each other. Taking these directions as axes, the resultant of the molecular forces acting upon a displaced molecule of the æther will be in the direction of the displacement if it is in the direction of these axes; but if in other directions, the force will not be in the direction of the displacement.

In uniaxal crystals the elasticities in two of the rectangular directions are taken to be equal; but in biaxal crystals the elasticities in the three rectangular directions are taken to be all different.

Proceeding from these considerations, M. Fresnel investigated the form of the wave-surface for biaxal crystals, and found that it must be considered as a single surface having two sheets, one within the other, and coming into contact at four points along the two optic axes. When the two optic axes coalesced into one, these sheets became the sphere and spheroid of Huygens.

Suppose as in a uniaxal crystal the point *o* in fig. 20 is a luminous point within a biaxal crystal, and *ab*, *cd* are the directions of the optic axes, along which the two rays travel with the same velocity. Then Fresnel's wave-surface in the plane passing through the optic axes gives a section like the figure, consisting of a circle and an ellipse, which intersect each other along the optic axes. When *ab* and *cd* come close together and coincide, the crystal comes to be uniaxal, and the circle and ellipse touch without cutting each other.

Fig. 20.



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[*] Mémoires de l' Institut for 1824, and Annales de Chimie et de Physique, tom. xxviii. p. 263.

The points *a, b, c, d* are the only points where the two sheets meet. The form of the surface about these points is the most important to examine, and we may obtain an idea of it by supposing a small part of the circle and ellipse near them to be turned round the axis, and thus generate the sheets. We see that the inner sheet will have a form something like an umbrella, as in fig. 21, and that the outer sheet will have a form like fig. 22. The point *b*, which is called a conical point, in the two figures being the point of contact, the rays which pass near the axes are said to have conical refraction.

Fig. 21.

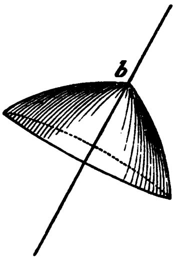
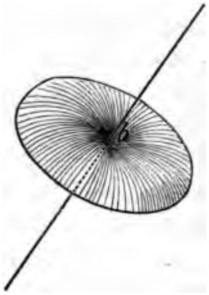


Fig. 22.



It is seen that the two sheets are continuous each up to the optic axis, and when we find that the outer one by experiment has a small round hole in it around the optic axis, which we may call an eyelet hole, it is clear that Fresnel's wave-surface does not represent the true luminiferous surface in biaxal crystals.

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Carbonate of lime in another crystalline form is again the best substance for experiments on the nature of the double refraction in biaxal crystals, on account of its strong double refractive power; namely, in the form known as arragonite or prismatic carbonate of lime. It is a much more rare mineral than the rhomboidal carbonate of lime, and has often the form of hexagonal rhombic prisms. The order of the crystallization is generally reversed in each prism, or they are what are called macled crystals. The prism, when cut perpendicularly, generally exhibits three portions, of which a middle portion lies between parallel planes, and the two parts, one on each side of it, have reversed crystallizations to that of the middle part. For these reasons it is difficult to obtain large pieces of one order of crystallization. When there is sufficient breadth of one order of crystallization, the phenomena discussed further on are well seen, with a thickness of half an inch.

The axes in arragonite within the crystal are inclined* 18° 18′, and the line bisecting this angle is the axis of the prism. Now outside the axes the double refraction approximates to that in uniaxal crystals, and it is within this angle and near the optic axes that we must examine the double refraction, in order to determine the peculiarities of the luminiferous surfaces. In order to do this we must premise what is well known in geometrical optics, namely, that if a bright object is placed before an opaque screen with a small hole in it, as for instance the flame of a candle at A in figure 23, before the small hole B, then on a screen, such as a card behind the hole, we have formed an imperfect inverted image *a* of the object A, as in fig. 23.

Let the hole B be as in fig. 24, a minute pin-hole in tinfoil covering the first surface of the piece of arragonite, cut perpendicularly to the line bisecting the optic axes, and the second surface covered with a slight film of milk which has dried upon it, for a screen to receive the images *a* and *b* of the flame of a candle at A.

Fig. 23.

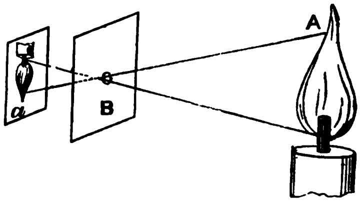
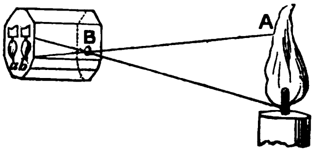


Fig. 24.



Then trying the experiment in a dark room, and using a magnifying eye-lens, we see generally two inverted images of the candle-flame upon the film of milk, arising from the double refraction. Turning the crystal carefully about we see a series of images, like those in fig. 25, in and near the plane of the optic axes for the given aperture B of fig. 24.

At the middle point between the axes we have the two images coinciding as at *ab*. On either side of it the images separate, as *a* nearer and *b* further from the single middle image. On coming to the optic axis the image *b* becomes diminished and distorted, whilst the image *a* becomes as *a*′ enlarged, and having in its middle a dark circular space, with the diminished image of the series *b* in its center. On passing beyond the optic axes we have the two images *a* and *b* again, but *a* has now passed beyond *b*, and so continues in other parts of the crystal.

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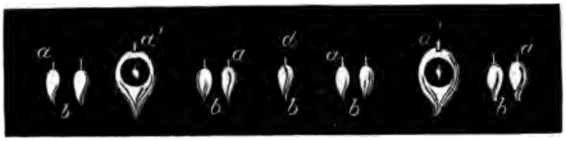
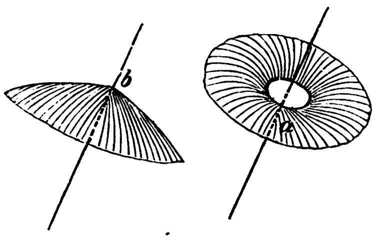
* Herschel on Light, art. 1124; Brewster's reply to Rudberg, Phil. Mag. for August 1832; and Rev. H. Lloyd "On the Phænomena of Light in passing through Biaxal Crystals," Phil. Mag. for February 1833.

Fig. 25.



Now at the optic axes the dark space within the enlarged image *a'* receives no light from the rays which form the series of images marked *a*, and hence the luminiferous surface is not continuous in this part; and the image of the series marked *b* in the middle of this space being contracted and distorted, shows that the other luminiferous surface at the optic axis is not of continued curvature, but forms a conical point. The luminiferous surfaces at the axes are as in fig. 26, where the conical point *b* and the center of the eyelet-hole *a* are along the optic axes, drawn through the aperture B of fig. 24.

Fig. 26.



Fresnel's wave-surface for biaxal crystals, therefore, does not represent the facts, and as no other form has been imagined possible on the undulatory theory of light, we have here a strong argument against it.

These points will require to be examined again when we discuss the law of the polarization of the rays in biaxal crystals.

---

At the commencement of the Chapter it was stated that many substances, crystallized and uncrystallized, have only ordinary refraction. A feeble double refraction is acquired by these substances,—by unequal heating or cooling, by pressure, by bending, or generally by any means which place certain of their atoms in unequal constraint with the rest. Many crystals of this class are also found, when irregularly crystallized, to possess a small double refraction. The existence of this double refraction is generally rendered visible by interference in the polariscope, but glass has been made by great compression to show two images of a point. This subject will be found discussed again under the heads of Polarization and Interferences.

The following table contains the names of some of the more common double refracting substances: for a more complete list see Brewster's 'Optics,' edition of 1853, pp. 194 & 200.

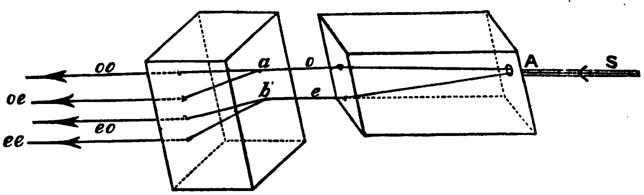
| Uniaxal crystals. | Biaxal crystals. |
|---|---|
| Carbonate of lime, or Iceland spar.<br>Nitrate of soda.<br>Tourmaline.<br>Chlorate of soda.<br>Quartz crystals.<br>Sapphire.<br>Ruby.<br>Emerald.<br>Beryl.<br>Hydrate of magnesia.<br>Prussiate of potash.<br>Phosphate of ammonia and magnesia.<br>Ice, certain crystals.<br>Mica, certain kinds. | Nitrate of potash.<br>Mica.<br>Arragonite, or prismatic carbonate of lime.<br>Borax.<br>Sulphate of magnesia.<br>Sulphate of zinc.<br>Sulphate of magnesia and soda.<br>Topaz.<br>Sugar.<br>Phosphate of soda.<br>Citric acid.<br>Tartaric acid.<br>Chlorate of potash.<br>Sulphate of potash.<br>Carbonate of soda.<br>Sulphate of lime or selenite.<br>Sulphate of iron. |

## CHAPTER II.

### ON THE POLARIZATION OF LIGHT.

The action of a rhomb of calc-spar on a beam of light was explained in the last chapter to have led to the theory of the *polarization* of light. It was found that a beam of ordinary light was refracted into two beams within a rhomb of calc-spar of equal brightness; but when these beams fell upon a second rhomb, though they were generally *each* refracted into two beams, yet they were not always so, for in certain relative positions of the crystals the second crystal did not separate the two first refracted beams again; and also when they were separated *each* again into two, making four beams emergent from the second crystal, they were commonly in pairs of unequal brightness, so that it was clear the two beams furnished by the first crystal had received some modification which caused them to be differently acted upon by the second crystal to what they had been by the first. This modification led Newton to the theory, that the doubly refracted rays had different properties on different sides, or were brought to a state of polarization by being doubly refracted, and the phenomena exhibited when these polarized beams were refracted by a second rhomb thus depended upon the relative positions of the sides of this rhomb with the sides of the polarized rays.

Fig. 27.



In fig. 27, let SA be a small beam of light passing through a small aperture A in an opaque cover on the first surface of a rhomb. Let *o* be the ordinary and *e* the extraordinary beam after emergence from it. Let again these fall on the second rhomb at *a* and *b*, and generally each will be refracted into two beams as in the figure, and after emergence we shall have—

A beam *oo* which has undergone ordinary refraction at both rhombs.

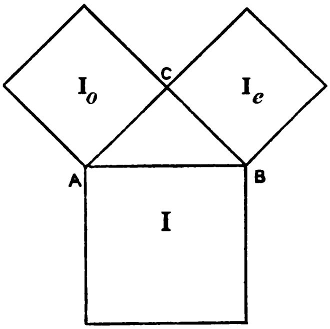
A beam *ee* which has undergone extraordinary refraction at both rhombs.

A beam *oe* which has undergone ordinary refraction at the first, and extraordinary refraction at the second rhomb.

A beam *eo* which has undergone extraordinary refraction at the first, and ordinary refraction at the second rhomb.

The law of Malus* for the brightness or intensity of the emergent beam, neglecting the loss by reflexions at the surfaces, absorption within the rhombs, &c., is as follows. Let I, the intensity of the incident beam, be represented by the area of a square on the line AB (fig. 28), and let ABC be a triangle with a right angle at C, and angles each half a right angle at A and B. Draw squares $I_o$ and $I_e$ on the equal sides AC and BC, then the areas of these squares will be equal and represent $I_o$ the intensity of the ordinarily refracted beam, $I_e$ that of the extraordinarily refracted beam; and by geometry $I_o$ and $I_e$ together are equal to I. This is the foundation of the resolution and composition of light.

Fig. 28.



Now the ordinary beam ($I_o$) is, *by definition*, said to be polarized in the *principal* plane of the rhomb, and the extraordinary beam ($I_e$) to be polarized in a plane *perpendicular* to the principal plane. The rhomb may be turned round in any way and the same result of two equal beams will be found, so that it is said a beam of common light is equivalent to two beams polarized in any two planes at right angles to each other, the sum of whose intensities equals the intensity of the original beam.

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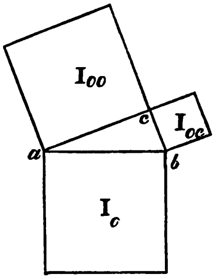
* Mémoires d'Arcueil, tome ii. for 1809, page 143.

When these beams, whose intensities are $I_o$ and $I_e$, fall on the second rhomb and again undergo double refraction, they are said to be analyzed again into new planes of polarization parallel and perpendicular to the principal plane of the *second* rhomb. Let $I_{oo}$, $I_{oe}$, $I_{eo}$, $I_{ee}$ be the intensities of the emergent beams *oo, oe, eo, ee* in fig. 27 respectively.

Take a square on *ab* (fig. 29) to represent the intensity $I_o$, and let *abc* be a triangle with a right angle at *c*, and let the angle *bac* be the angle between the principal planes of the two rhombs, which is also the angle between the plane of polarization of $I_o$, and the principal section of the second rhomb. Draw squares on the sides *ac* and *bc*, then the square on *ac* represents the intensity $I_{oo}$, and that on *bc* represents $I_{oe}$, and their sum equals $I_o$. The same construction applies to the intensities $I_{eo}$ and $I_{ee}$, whose sum equals $I_e$, remembering that the angle *abc* is now the angle between the plane of polarization of $I_e$ and the principal plane of the second rhomb. From this we see that $I_{oe}$ equals $I_{eo}$, and $I_{oo}$ equals $I_{ee}$, so that, as before remarked, the four beams are in pairs as to brightness.

Fig. 29.



When *ac* coincides with *ab*, then *bc* vanishes, and $I_{oo}$ equals $I_o$ and $I_{oe}$ is zero; and in like manner $I_{ee}$ equals $I_e$, and $I_{eo}$ vanishes, that is, when the principal planes of the two crystals are parallel, there are an ordinary and an extraordinary beam formed only by the second rhomb. Again, when *bc* coincides with *ab*, or the principal planes of the rhombs are at right angles to each other, then *ac* vanishes, and the extraordinary beam has the intensity $I_{oe}$ equal $I_o$, and the ordinary beam in the first crystal becomes the extraordinary one in the second, $I_{oo}$ vanishing; also the other beam $I_{eo}$ equals $I_e$, and $I_{ee}$ vanishes, so that the extraordinary beam in the first becomes the ordinary beam in the second crystal.

When the angles *abc* and *bac* are each half a right angle, the intensities of the four emergent beams are equal.

These results of Malus's law are in accordance with experiments.

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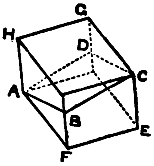
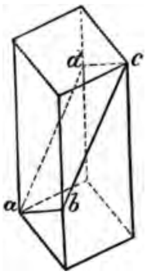
Amongst the apparatus formed with calc-spar is a rhomb made of the crystal and glass, called a double image rhomb. An angular portion is cut from a rhomb of calc-spar, such as ABCDEF in fig. 30, and an equal piece, ABCDGH, of plate-glass is made; and the two, being reversed, are cemented together with Canada balsam, which has nearly the same refractive index as glass. Now a ray of light entering the calc-spar is separated into two, and these pass through the cementing film and into the glass with very little deviation, but on emerging from the outer surface of the glass there is not the accurate reverse refraction to that at the first surface of the calc-spar, and hence the two emergent rays are not parallel, but separate the more as they are further from the rhomb. The glass nearly corrects the prismatic colour for one of the rays, but the other is considerably coloured.

Fig. 30.



Another and more useful compound rhomb was invented by Mr. Nicol. A long rhomb of calc-spar, as in fig. 31, is cut into two angular portions, as in fig. 31, by a section *abcd*, and the two parts are then cemented together again. Now the two refracted rays falling very obliquely upon the film of cement, one of them is *reflected totally*, and thrown aside according to the rules of geometrical optics, but the other is transmitted. In this manner the rhomb furnishes a beam of light polarized in one plane, and is one of the most useful pieces of polarizing apparatus.

Fig. 31.

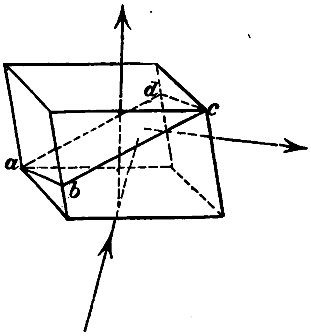


Nicol's rhomb will be found continually described as part of the apparatus in the experiments in the interference of polarized light; and there are also many delicate experiments, in which the state of the polarization of certain rays has to be tested, where it would be employed.

Where one of the rays is to be thrown aside by suffering total reflexion, this can be accomplished with much less acute prisms when a plate of air is left between the surfaces of the section *abcd*, instead of cementing them, and then a much broader beam of polarized light can be obtained, as in fig. 32; but then there will be a considerable loss of light from reflexion, in the transmitted beam, at the internal surfaces.

The advantage of these compound rhombs arises from their furnishing bright beams of polarized light without colour.

Fig. 32.



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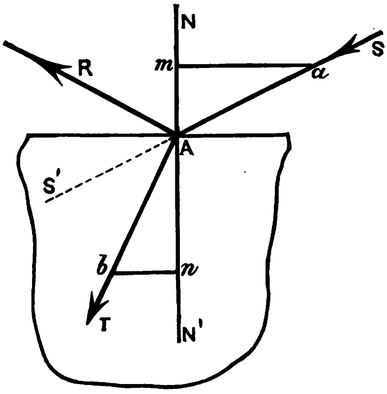
The discovery of the polarization of light by reflexion at the surfaces of transparent bodies by M. Malus* in 1808, whilst examining the rays of the setting sun reflected from the windows of the Luxembourg Palace, with a rhomb of calc-spar, was the commencement of a new æra in Physical Optics. We have seen that a beam of common light gives two beams of *equal* intensities after emergence from the rhomb, but the light reflected from the windows giving them of unequal intensities, Malus saw that it had become modified by the reflexion. Pursuing his experiments, he found that at a certain angle the reflected light was completely polarized in the plane of incidence, having the properties of the ordinary beam transmitted by calc-spar.

Dr. Brewster†, in 1815,



* Mémoires d'Arcueil, ii.

† Phil. Trans. 1815.

discovered the law of the polarizing angle to be as follows:—Taking again fig. 4, as employed to discuss the law of the sines, SA being the ray of incident light, AR the reflected, and AT the refracted ray; making also A*a* equal to A*b*, and drawing perpendiculars *am* and *bn* upon the normal NAN′ to the refracting surface at A; then the reflected light in AR is completely polarized in the plane SAR, when *bn* equals A*m*, or *am* equals A*n*, and the angle RAT between the reflected rays and refracted rays is then a right angle.

In trigonometrical language it is said the tangent of the polarizing angle SAN equals the refractive index of the transparent substance; and the angles SAN, TAN′ together make a right angle.

For plate-glass, the angle SAN becomes the polarizing angle when it is 56½° nearly, and for water when it is 53° 10′ nearly.

When the refracting body is a plate with parallel plane surfaces, the refracted ray AT is partly transmitted in TV, and partly reflected in TA′ (fig. 33). The part in TA′ is again partly reflected at A′ and partly transmitted in A′R′; and so onwards for many reflexions at the second surface of the plate. Now the emergent rays as A′R′ are all polarized in the plane of incidence SAR when AR is so polarized. For this reason, when we wish for a brighter polarized beam, we use the reflexions from both surfaces of a plate; and often also piles of several plates packed in a convenient frame.

Fig. 33.

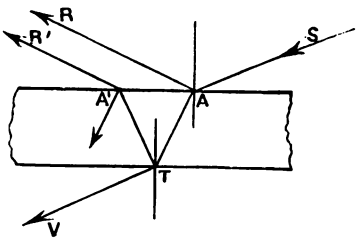
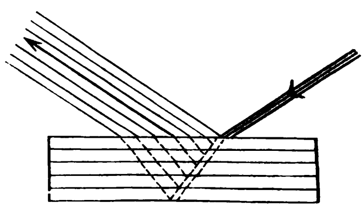


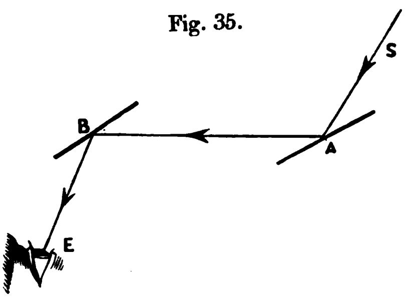
Fig. 34.



In this way a number of pieces of good window-glass, placed as fig. 34, form an almost essential piece of apparatus to those engaged in optical studies. A beam of polarized light is thus easily procured of great breadth and brightness. It has the disadvantage, however, that the dust and imperfections upon the surfaces of the plates partly depolarize the light, and this is of consequence in some delicate experiments.

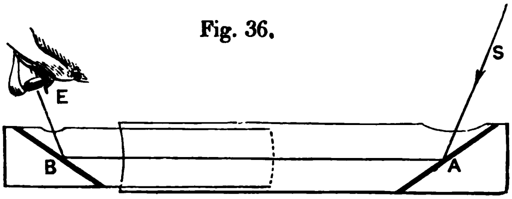
The transmitted ray TV is not completely polarized, but exhibits, when examined with a rhomb of calc-spar, two rays of unequal intensities, that being brightest which is polarized *perpendicular* to the plane of incidence. The transmitted ray becomes more and more nearly polarized *perpendicularly* to the plane of incidence, as the angles of incidence and emergence are increased, or as the rays emerge more nearly parallel to the surface of the plate.

Fig. 35.



Experiments showing many of the properties of polarized light may be made with pieces of window-glass and very simple mounting. Suppose in fig. 35 that a ray of light SA falls at the polarizing angle 56½° of incidence upon a plate of glass at A, and then the reflected ray AB, which is polarized in the plane SAB, falls upon a second plate at B at the same angle, and is then reflected to the eye at E. The brightness of the light reaching the eye depends upon the angle between the planes SAB and ABE. If we turn the plate B round the line AB until the angle between those planes is a right angle, then *no light whatever* reaches the eye E. This result arises thus: the plate B reflects light only polarized in the plane of incidence at B, and the plate A furnishes only light polarized in the perpendicular plane, of which no part can be analyzed to be in the plane EBA, by Malus's right-angled triangle.

Fig. 36.



The plates A and B are easily mounted in two tubes of pasted paper, as in fig. 36, and packed at the proper angles; a large hole being cut in one tube to allow the incident light through its center to fall at the polarizing angle at A, and a smaller hole for an eye-hole to allow the light reflected at the polarizing angle at B to pass to the eye E. The eye-tube turning inside the other allows the above-described experiment to be easily tried.

Many of the splendid experiments of the interference of light exhibited by crystalline plates, can be tried also with such an apparatus, with the requisite additions; though more conveniently often in other ways.

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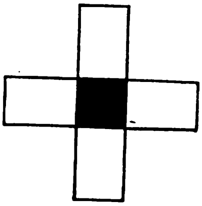
The Tourmaline, a mineral of frequent occurrence, and often associated with mica, furnishes a valuable optical apparatus. This mineral is a uniaxal crystal, and found of various colours in long prisms; the dark varieties have the property, when cut into thin plates parallel to the axis of the prism, of transmitting only light polarized *perpendicularly* to that axis. The thickness necessary to polarize completely the transmitted light depends upon the darkness of the tourmaline. The dark green and brown varieties require often to be not more than $\frac{1}{10}$th or $\frac{1}{20}$th of an inch in thickness, and the transmitted light is often polarized nearly completely by a thickness of $\frac{1}{40}$th or $\frac{1}{30}$th of an inch. The thinner plates are often desirable from their transmitting much more light than the thicker ones, although it is not perfectly polarized. The neutral tint tourmalines are also desirable from their not affecting the appearance of the interference phenomena so injuriously as the others, although the plate may not completely polarize the transmitted light. Plates cut and polished, sufficiently large to be very useful, can be purchased for a few shillings.

The advantage of the tourmaline plate is, that the eye can be brought very near the object to be examined by polarized light; and its disadvantage is that the transmitted light is strongly coloured, the colourless tourmalines not having the property of absorbing light polarized parallel to the axis of the prism, as the coloured ones have.

If two plates of tourmaline, sufficiently thick to completely polarize the transmitted light, are crossed upon each other, as in fig. 37, the part where they cross appears perfectly opaque, whilst the other parts of each appear transparent.

Fig. 37.



The property of unequally absorbing the polarized rays is possessed by many substances, which have been described by Dr. Brewster in the Philosophical Transactions for 1819.

Lately Dr. Herapath has discovered a very remarkable salt, the iodide of quinine, which possesses in so high a degree the property of absorbing one of the polarized rays, that he calls the crystalline plates artificial tourmalines. For the method of preparing and mounting these artificial tourmalines, see Dr. Herapath's papers in the Philosophical Magazine for May 1854, and previous Numbers.

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There are certain *compound* beams of polarized light which have had considerable attention bestowed upon them, from the interesting phenomena exhibited by them in the early experiments of MM. Arago and Biot; and afterwards from the important discussions of M. Fresnel upon the way in which such beams arise in certain cases; and upon their representation according to the undulatory theory of light. It will be seen in the next Chapter that these beams are really subject to the general laws of the interference of light, and will be best understood when those laws have been fully developed.

We have seen that M. Malus first proposed a rule for expressing the decomposition of beams of light polarized by passing through a first rhomb of calc-spar, on their separation again on being refracted by a second rhomb. Now the rule for compounding together again such beams by a reverse process, must be the converse of M. Malus's law; and as far as intensities and polarization only are concerned, this law furnishes all that is required. When, however, the beams have come from a common origin, the laws of interference must be considered at the same time. This subject therefore will be considered again in the Chapter on Interference; at present we shall only take the properties of these compound beams as of peculiarly polarized light.

If two *equal* beams of light, polarized in planes at *right angles* to each other, have their luminiferous surfaces one *in advance* of the other *one-fourth* of an interval of light (one-fourth the breadth of a wave in the undulatory theory), they constitute what is called *circularly polarized light*. On being analyzed by a rhomb of calc-spar, a tourmaline or other analyzer, it exhibits all the properties of common light; but in certain interference experiments the results are very different, and very interesting. In the undulatory theory also there is considerable interest attached to such beams, for it is easily shown that the particles of the hypothetical æther must be performing their vibrations in circles, whose planes are perpendicular to the rays of light. By compounding the equal rectilineal vibrations which have an interval of one-fourth the breadth of a wave, there results a circular path for each particle, and a series of particles originally in one straight line, become arranged in the form of a helix, or as if placed at regular distances along the thread of a screw.

In other circumstances, the compounding the vibrations gives rise to *elliptic* vibrations, and the light is said to be elliptically polarized. When the difference of the paths is half an interval, the two beams compound into one, which is plane polarized. These points have been verified by M. Arago*.

M. Fresnel has shown two ways in which circularly polarized light may be produced. In one of these a film of mica (which is a biaxal crystal) is chosen of such thickness that one of the two double refracted rays is retarded one-fourth of an interval behind the other, and this film is attached to the support, which carries a tourmaline, by some kind of cement, in such position that the plane of polarization of the light transmitted by the tourmaline may bisect the *angle between* the planes of polarization of the two rays emergent from the mica. A pair of these circular polarizers are desirable apparatus, as will be found in the Chapter on the Interference of Polarized Light, and they can be made by those who possess the tourmalines and pieces of plates of mica, by care and patience. The mica must be split with a penknife into exceedingly thin slips, and these must be attached with wax to the support of the tourmaline, and turned about until the two conditions are found to be obtained, namely, the mica plate of *right thickness*, and in a *right position*. These are sufficiently nearly produced when the combination, on being used as an analyzer, the tourmaline towards the eye, with any form of polarizer, shows very little difference of brightness for different positions on turning it round. It can never produce the required effect perfectly in white light, because the one-fourth of an interval is considerably different for different colours of the spectrum*, but may be accurate for some one tint.

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* See Herschel on Light, art. 996.

In the other method, a rhomb of glass of a section like fig. 38 is used under the name of Fresnel's rhomb. The acute angles at *a* and *c* of the section of the rhomb are 54½°, and the light entering the first surface *ab* perpendicularly, and emerging in like manner from the second surface *cd*, is twice totally reflected within the rhomb, namely at A and B. M. Fresnel found that light passing through the rhomb in this manner is analyzed into two portions, one polarized in the plane of the reflexions, and the other perpendicular to it; and the latter is retarded one-fourth of an interval behind the former, whatever be the colour of the incident light. Now when this rhomb is placed, as in fig. 39, to receive plane polarized light, as for instance that reflected at the polarizing angle from glass, and the plane of the two reflexions is inclined 45° to the plane of the polarization of the incident light, then the light emerging from the rhomb is circularly polarized light *for all colours*.

Fig. 38.

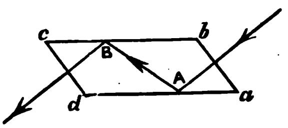
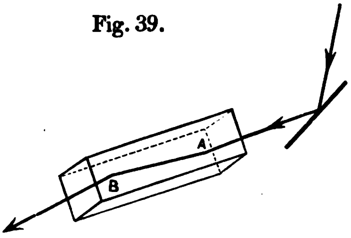


Fig. 39.



For common use, the rhomb may be made of ordinary plate or flint-glass, and it is not necessary that the angles at *a* and *c* should be exactly 54½°. The author has many rhombs of common flint-glass with different angles from the lowest which would give total reflexion at A and B to high angles, and two of common plate-glass, one with the lowest angle, and the other with the angles 54½°; these show the light to be most perfectly circularly polarized, when the angles *a* and *c* are the lowest possible for total reflexion at A and B, namely, in plate-glass about 42°, and that it is elliptically polarized with higher angles. Common plate and flint-glass are not, however, adequate materials to enable the experimenter to form a certain judgment on so delicate a point of physical optics, since such glass is never homogeneous.

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* See the table of the breadths of the intervals in the next Chapter.

It has been stated that the plane of reflexion within the rhomb must be inclined 45° to the plane of the polarization of the incident light in fig. 39, but this inclination may be to the right hand or to the left hand, and the emergent light is called *right-handed circularly polarized light*, or *left-handed circularly polarized light* accordingly. These distinctions will be noticed again in discussing the properties of quartz crystal.

When a beam of ordinary light was incident upon a *metallic* polished surface, and the reflected beam was analyzed by a rhomb of calc-spar, it was found by Malus that the two beams, analyzed in the plane of incidence, and perpendicular to it, are generally of different intensities, but are never reduced to one beam, as in the case of transparent bodies when the reflexion takes place at the polarizing angle. The maximum difference of the intensities has been found by Sir D. Brewster to occur at an incidence between 70° and 80° for many metals and galena, and the light polarized perpendicularly to the plane of incidence is more copiously absorbed by the metal than that polarized in the plane of incidence.

If a plate of polished steel be substituted for the rhomb in fig. 39, so that the light from the polarizer may be reflected by the steel at an angle of incidence of 75°, and the plane of reflexion be inclined 45° to the plane of the polarization of the incident light, the light reflected by the steel has become elliptically polarized.

The interference phenomena seen in circularly polarized light will be found described in a future chapter, and those in elliptically polarized light are analogous to them, and may be seen by mounting the blade of a new eating-knife in the above manner in the polarizing apparatus.

M. Jamin*, with a refined apparatus and delicate method of experiments, has found that almost all solid substances polarize light incompletely, and that they transform plane polarized light into elliptically polarized light by reflexion. He has found that those substances, whose index of refraction is greater than 1·46, advance the phase of the component ray polarized in the plane of incidence; and those which have their refractive index less than 1·46 retard it. Those which have the refractive index 1·46 only, give accurately plane polarized light at the polarizing angle.

The polarization of the two beams given by biaxal crystals, in the neighbourhood of the optic axes, is very interesting and singular. The *law* of the polarizations was deduced from analogy with uniaxal crystals by M. Biot, as well as an approximate rule for the distance between the two luminiferous surfaces at any given points near the axes. This latter will be required to be considered in discussing the interference phenomena.

At the close of the last chapter the forms of the luminiferous surfaces within a biaxal crystal were traced generally. We have now a similar experiment to try, with the piece of arragonite having a piece of tinfoil attached to its first surface, with a small pin-hole in it, and to examine the polarizations of the two images formed upon its second surface, of a flame of a candle before it. The film of milk upon the second surface must now be dispensed with, since it depolarizes the light. The analyzing apparatus should consist of an eye-lens attached to a tourmaline or Nicol's rhomb, and the direction of the plane of polarization should be marked upon them.

Taking the series of images of the candle upon the second surface, as in fig. 25, and supposing them represented with others in fig. 40, we find the central image, which is composed of two images, to appear as of common light. When the images appear separated in the plane of the optic axes CD, we find the one nearest the central one to be polarized in the plane of the optic axes, but it is marked *a* in fig. 25 within them, and *b* beyond them. To enable us to trace these changes, a small line — or | is placed near each image in fig. 40 to indicate its plane of polarization. The further image of a pair in the plane CD is polarized perpendicular to that plane, but in fig. 25 it is marked *b* within the axes, and *a* without them. We saw that the enlarged image *a'* at the optic axes arose from the passage of an image *a* from within to beyond the image *b* at those points. Again, taking a plane through the small hole on the first surface of the crystal, and through the central image perpendicular to the former CD, as EF (fig. 40), and examining the polarization of the images formed in it, we find that the *inner* image now belongs to the series marked *b* in fig. 25, and its polarization is in the plane EF; also that the outer image which belongs to the series *a* is polarized at right angles to it. The dotted lines in fig. 40 show how the series of images are connected through the intermediate positions.

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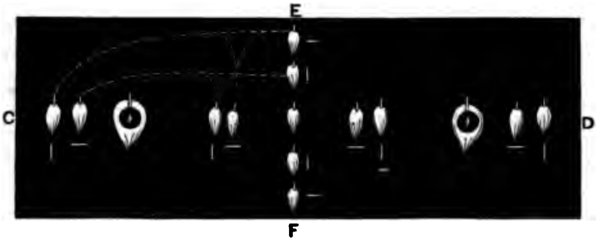
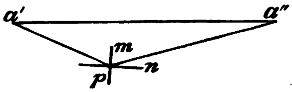
* Annales de Chimie et de Physique, 1850, vol. xxix. p. 304.

Fig. 40.



All these changes of the planes of polarization are given by the law of Biot*, as follows: take two planes, one passing through the small aperture on the first surface, a given position *p* of the image on the second surface in fig. 41, and one of the optic axes *a'*; and the other plane passing the first two points, and the other optic axis *a''*. Let these planes meet the second surface of the crystal in the lines *a'p* and *a''p*; then the plane of polarization of one ray bisects the angle between the planes, as indicated by the line *pm* in the figure, and that of the other is perpendicular to it, as indicated by the line *pn*.

Fig. 41.



On examination, this law will be found to represent all the circumstances, and it shows how the enlarged image *a'* (fig. 25)

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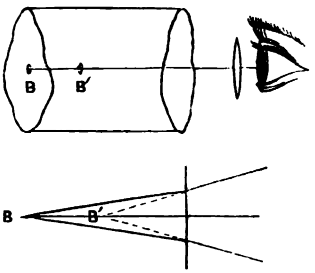
[*] Précis Elémentaire de Physique, vol. ii. p. 491.

at the optic axes, with its central dark circle, has its planes of polarization at right angles to each other on its opposite sides; or whilst we pass through *two* right angles around its center, the plane of polarization has passed through *one* right angle. The diminished image in the middle of the dark space appears as if of common light, or is polarized in all planes.

In another method of observing, we may trace the law of the polarization at the conical point, and its connexion with that at the edge of the eyelet-hole. The appearances are very interesting, and considerable mistakes have been made with respect to them*.

We must first premise a proposition of geometrical optics:— If fig. 42 represents a piece of a refracting substance, such as glass, with any point B on the further surface, and we look at this point through an opposite *plane* surface, we see a virtual image B′ of B apparently within the medium, or nearer to the eye by the distance BB′. The distance BB′ is about one-third the thickness for glass, and about one-fourth the depth for water, as may be easily seen in a glass of water by looking downwards into it.

Fig. 42.



Now the rays after emerging fall upon the eye-glass, and enter the eye as if they had come from B′, as in the lower figure. Applying this to a piece of arragonite, it enables us to trace the positions of the centers from which the rays diverge, after emerging from the crystal, and allowing for the refraction, we trace the forms of the luminiferous sheets of the surfaces in the crystal.

The annexed figure 43 is the analogous one to fig. 40, for this method of observing with the eye-lens cemented to a tourmaline plate; using a minute hole in a piece of tinfoil on the first surface for the spot B of fig. 42.

We see the middle spot to be composed of two, at different depths apparently, in the crystal, and polarized at right angles to each other. On looking a little obliquely, we see on each side, when the two images are separated, that they are polarized like the images before discussed as indicated by the lines — and | , drawn through the images, the dotted lines showing their connexion.

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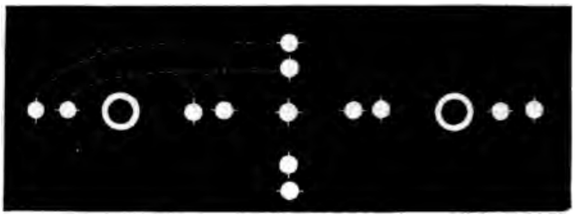
* Philosophical Magazine for May 1841, p. 343.

Fig. 43.



When we come near the directions of the optic axes, the images turn round each other in a singular way on slight changes of the inclination of the crystal, and when we look accurately in the direction of an optic axis, the two images run each into a luminous ring, as in the figure. On examining carefully, we see that there are two rings in reality, at somewhat different depths in the crystal, and that each series of images gives its own ring. On bringing the eye-lens nearer to or further from the crystal, we see that these rings are formed by two conical pencils of rays, one of which diverges to form the rays around the eyelet-hole, and the other converges to form the conical point in its center, as they emerge from the second surface of the crystal.

Fig. 44.

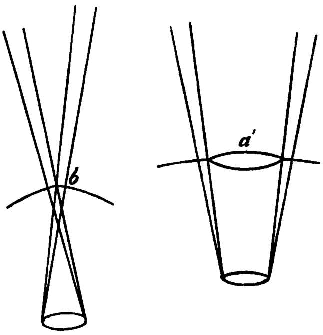


Figure 44 shows how the rays diverge from a ring to form the eyelet-hole $a'$ in the figure, and converge from a ring to form a conical point $b$ in the other figure. Now the superposed rings considered as one, are completely polarized, but at each point in a different plane; so that with the eye-glass and its analyzing tourmaline, one part appears always black; and as we turn the tourmaline *half* round, the black spot runs round the *whole* circumference of the compound ring. That the two series of cones, diverging and converging, are polarized according to this law, can be seen by drawing the eye-lens from, or pushing it nearer to the crystal, but some care is required to notice where the two series of cones overlap, and appear then like common light.

The double refraction of bodies being connected with their crystalline forms, evidently arises from the properties and arrangement of their ultimate atoms. The caloric, which is a constituent part of the body, in any particular form, has evidently a great effect also; thus ice has but little less refractive power than water, although so much lighter specifically, its atoms having a crystalline arrangement, though at greater distances than in the state of water, have the properties of those of uniaxal crystals, whilst in the more dense state of water they only exhibit ordinary refraction. It was therefore to be expected that substances which exhibited ordinary refraction in some states, might in other states possess double refraction. This has been found with many substances, such as unannealed glass, ordinary glass which has been heated and cooled suddenly, glass under the action of powerful electro-magnets, or when subjected to pressure or flexure; gelatinous substances after drying rapidly, and transparent substances generally when their atoms are subject to unequal restraint. Crystals are frequently found which exhibit interference phenomena in polarized light very different from those of their normal state, and showing the crystallization to have proceeded irregularly. Under the influence of heat and cold they also exhibit change of optical properties. It is therefore evident that the single or double refraction depends upon the arrangement of the atoms of bodies, and changes with the change of arrangement.

In general, the existence of double refraction, or change of it, in the above-named cases is concluded by the phenomena of interference shown by them, but glass was subjected by M. Fresnel to so great inequality of pressure as to exhibit two rays from a single incident ray. Several liquids exhibit interference phenomena in polarized light similar to those seen near the optic axis of quartz, and which we conclude to arise from a like kind of double refraction. Amongst these liquids are oil of turpentine, solutions of sugar, of dextrine, of gums, &c. In these cases it is difficult to show how the atomic arrangement can produce the effects in every direction.

When the sky is clear, if the blue dispersed light be examined with an analyzer, it will be found generally to be more or less polarized; the maximum effect being about 90° from the sun. There are, however, several points of no polarization, or neutral points, of which a description will be found in Brewster's 'Optics,' edition of 1853, page 372.

If we look towards the sky when uniformly overcast through a Nicol's rhomb, with a little attention we perceive what have been called from their discoverer, the colour pencils of M. Haidinger. Although this is the best way to observe them, yet they may be seen easily in plane polarized light produced in other ways, when once the eye has recognized them. They appear as faint yellowish and bluish brushes at right angles to each other, sometimes one predominating, sometimes the other; the yellow being *in the plane* of polarization. The best way to succeed on first making the attempt, is to look steadily at the clouds through the rhomb, and then suddenly turn it round its axis through a right angle, when the brushes will almost invariably be seen.

There have been many attempts to explain a phenomenon so interesting in the physiology of the eye. The brushes being most distinctly seen when the plane of polarization has been suddenly turned through a right angle, leads to the following conclusions:—first, that of all the colours of the spectrum, the retina is the most sensitive to the straw-yellow rays in the plane of polarization, and most sensitive to the blue rays in the direction at right angles to it; secondly, that, as in many other cases, when the retina has been under any one impression for some time, it becomes less sensitive to it, and more sensitive to the complementary impression.

When light which is *plane polarized* is incident upon a transparent surface, the reflected light has its plane of polarization different generally from that of the incident light, and according to a rule discovered by M. Fresnel. This law will be found discussed mathematically in the Second Part of the present treatise.

# CHAPTER III.

## ON THE INTERFERENCE OF LIGHT.

In the introductory chapter the property of periodicity in light was explained, and the way in which it led, as a certain consequence, to interference. Newton, considering the luminiferous corpuscles to be emitted from luminous bodies without the property of periodicity, imagined that it was given to them each separately in certain cases of passing through transparent surfaces, or they were thus put into regularly recurring states to be easily reflected or easily transmitted when they arrived at another transparent surface. In this manner he gave an imperfect explanation of the colours exhibited by thin transparent plates and films, which was long received as an adequate explanation, from the want of critical examination. Fresnel showed that even as a solution of the colours of thin plates, this doctrine of *fits of easy reflexion and transmission* was inadequate, because it was evident that the light reflected at both surfaces of the film (such as a soap-bubble) was concerned in producing the colours seen in the reflected light.

It is needless therefore to examine further the Newtonian doctrine of periodicity*, or the way in which vibratory motions in an ætherial medium might communicate it, since it must now be admitted that *periodicity* is an essential and inherent property of light; and if light consists of luminiferous corpuscles, they must be emitted in surfaces or shells following each other in regular succession as waves follow each other, and at intervals which are always the same for the same colours of light. Such luminiferous surfaces of corpuscles meeting in a regular manner must interfere, but the interference would probably be of a different character to the mechanical interference of waves. If asked what would be the character of such interference, we may say it will be chemical, that is, it will involve higher and more varied mechanical principles than those supposed for vibratory and undulatory motions in an elastic medium. It appears that this chemical interference is our only resource when interference of light is demonstrated, and with circumstances which show that it cannot be undulatory interference.

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* See Newton's 'Opticks,' 3rd edition, p. 323.

The experiments in interferences may be classed under three heads,—*first,* those which require the interfering lights to come immediately from a luminous point; *secondly,* those which are seen in ordinary daylight; and *thirdly,* those which are seen only with polarized light.

The second class are often met with, presenting themselves spontaneously to the observer who recognizes them, and are generally the easiest to perform; but the first class are the simplest in their explanation, and so must be considered first.

The fundamental experiment of interferences, which may be said to have finally demonstrated that property of light, was discovered by M. Fresnel*. He considered that if the beam of light, radiating from one luminous point, were made into two beams by being reflected at two plane mirrors, they would be in like circumstances, and be in a state to interfere, having come from a common origin. On trying the experiment with the needful precautions, the interference was evident, and in circumstances where no other explanation could be given; hence it became a necessary property to be considered in every hypothesis of the nature of light. Having been discovered upon considerations of the undulatory theory of light, too little care was exhibited to learn whether the interference was really an undulatory interference or not. The points where the undulatory explanation fails will be pointed out in the propositions as they arise.

To form a luminous point we find the sunlight by far the best. If the sun shines directly through a convex lens of short focus, which may be one inch, one-fourth of an inch, or one-tenth of an inch, according to circumstances, as we want a stronger light, or require a smaller luminous point, we have an image of the sun formed in the focus, and the rays diverge again from this image as a luminous point. The magnitude of the image is found thus: the sun's angular diameter being about 32 minutes of a degree, the image at the focus F of the lens A subtends at the center of the lens the same angle. Now if the lens be of one inch focal length, the diameter of the image is one inch multiplied by the chord of 32 minutes, and equals .0093 of an inch, or $\frac{1}{107}$th of an inch. If we are experimenting at short distances from the luminous point, this may be considered too large, and we may use a lens of shorter focus. The luminous point is generally used in a darkened room, and sometimes, if the light must be thrown horizontally into the room, the mirror of a solar microscope would be used for this purpose, the framework with which it works being attached to the opening made in the window-shutter. For accurate measurements, an instrument called a *heliostat* would be employed to throw the sun's light always in the same direction, the movement of the mirror being performed by a clock*.

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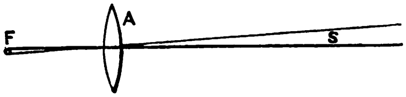
* Annales de Chimie et de Physique, 1819.

Fig. 45.



For many popular experiments a darkened room is not necessary, and a luminous point can be obtained much more simply than as described above. When the sun's light falls upon a *convex* mirror, the reflected light diverges from the image of the sun, formed by the mirror, which may be used as a luminous point. The mirror may be of any of the following forms, and should be placed upon a large piece of *black* cotton velvet. A convex mirror of highly polished speculum metal would be the best, but for ordinary use a silvered watch-glass, a white metal spherical button, a bulb of a thermometer, or in a good form the hollow silvered glass spheres sold as beads; and perhaps amongst these latter, the best of all are the hollow silvered spheres of glass, which are called *German lamps*, and sold at the toy shops to hang in Christmas trees. For experiments in diffraction, one of these may be very conveniently used.

To try the fundamental experiment of interferences, let F be the luminous point, such as the sun's image in the focus of the lens L. Let AB, AC be two plane mirrors inclined to each

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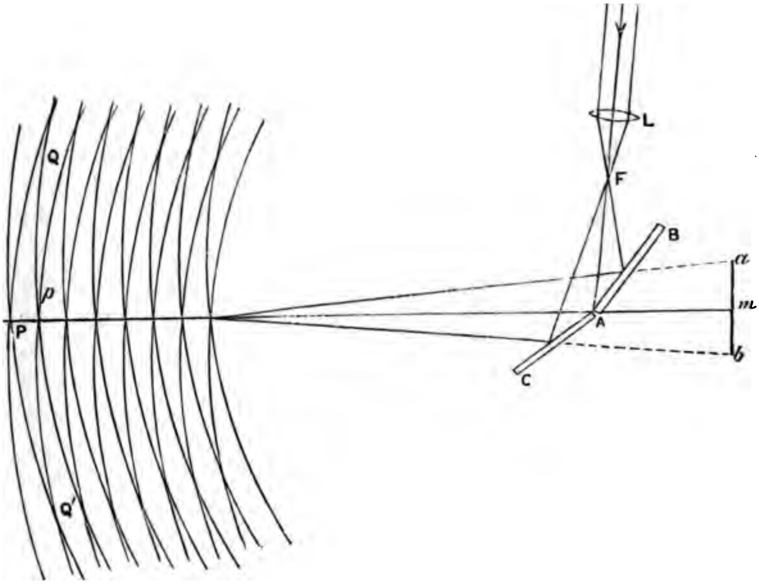
* For the construction of a simple heliostat, see Phil. Mag. for January 1833, p. 6.

Fig. 46.



other at a very small angle, or nearly in the same plane; then each mirror will give a virtual image of F, which is at an equal distance behind the mirror to what F is in front of it. Let *a* and *b* be their positions; then after reflexion the light will radiate as if coming directly from these images, and will be in a fit state to interfere. Draw P*m* a straight line bisecting perpendicularly the line joining *a* and *b*, then every point in it, such as P, will be at an equal distance from each of them, but points such as *p* out of the line P*m* will be at unequal distances from *a* and *b*. Now if the circular arcs at QP, Q'P represent luminiferous surfaces originating as if from *a* and *b*, the two series must interfere where they overlap, and in some places destroy each other's effect, but in other places strengthen each other.

Along the line P*m* the luminiferous surfaces will meet in the same state, and according to the undulatory theory will strengthen each other, and produce a brighter light, whatever be the interval between the successive surfaces. On each side of this line the effects will be symmetrical, so that it is the place of central interference for all colours; but the distances on each side where the luminiferous surfaces will be again in a like state of accordance, represented by the crossing of the arcs in the figure, will depend on the interval between them, which is different for different colours, and for red is half as much again as for violet light. We see that on each side of P*m* the places of accordance will occur in regular succession, and in the undulatory theory form a series of bright bars, if the light were received on a screen; but the distances between them would be least for violet light, and greatest for red, and intermediate for the other colours of the spectrum, so that the coloured bars would be separated except along the middle line P*m*. This, in experiments, serves to distinguish the central bar, namely, that the other bars are coloured symmetrically on each side of it.

Now half-way between two places of complete accordance there must occur a place of complete discordance, where the difference of distances from *a* and *b* is $\frac{1}{2}$ an interval, or $\frac{3}{2}$, or $\frac{5}{2}$, or $\frac{7}{2}$, &c. of an interval, and according to the undulatory theory there would be complete darkness in these places. Between these and the places of complete accordance would occur all intermediate states of discordance and accordance. From these premises it will be seen that there would be a series of bright bars shading into dark ones, and all more or less coloured on their edges except the central one.

Instead of receiving this interfering light on a screen, it is far the best way to observe it in the method of M. Fresnel, with a magnifying eye-lens in the air; for the eye-lens shows to the eye what occurs in the air at its focus, and with much greater brightness and certainty than can be seen on any screen.

Now whether the mirrors be of highly polished speculum metal or glass blackened at the back, the *central* bar is seen to be a *black one*, with the colours symmetrical on each side of it, when the sun's light is brightest, and the atmosphere free from thin clouds; but it is frequently doubtful when there are thin cirro-stratus clouds in the air, and the author has seen it undoubtedly a *bright one* when the sun was near setting. It has been seen certainly a bright bar when the luminous point was formed at a hole in a thin plate of metal, and the light which had grazed the edge of the hole was used.

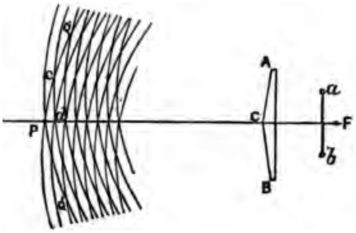
The existence of a central *black bar* in normal circumstances is certainly inconsistent with an undulatory theory of light, and this was the first experiment which shook the author's confidence in that theory. It appears, however, that light is so modified in passing through haze, or at an opaque edge of a small hole, as to acquire an anatropy or inversion of properties; and we shall find frequently that this modification must be remembered, as it continually occurs.

The mirrors are best formed of highly polished speculum metal, but these are difficult to obtain. Mirrors of glass are, however, easily made and quite sufficient. Plate-glass, if optically polished, is the best sort; but if not at hand, the best parts of common window-glass are far preferable to imperfectly polished plate-glass. Pieces of window-glass should be examined with a magnifier until a piece is found free from ridges, spots, and other imperfections, and as flat as possible. Taking a piece of this about 1½ inch square, we must get a cut from a diamond made across its middle parallel to two sides, and heating it over the flame of a candle, rub a coating of black sealing-wax on the side which is the least perfect, and which is to be the back. This coating of black sealing-wax, melted on the glass, takes away the reflexion of the back surface; and breaking the piece now at the diamond cut, we have two mirrors, of which the edges can be brought close together.

These glass mirrors must be mounted in a wooden frame, so that when they are got into their proper position they will remain so. The two edges at the diamond cut being placed together accurately, the mirrors must be inclined to one another, so that when we look past their junction at a distant window-bar, its images may appear slightly separated. Now the distances of the luminiferous surfaces, as will be seen in the table accompanying the articles upon the colours of thin plates, average about one fifty-thousandth part of an inch, and if the edges are not accurately together, the interference may not be seen. On account of the mixture of colours, only ten or twelve bright bars at most are visible in ordinary sunlight; and if the edge of one mirror projects only one-thousandth part of an inch above the other, it may displace the central bars the breadth of many bars out of the way, and no interference will be seen. To get the two edges accurately together, pass the finger-nail across the junction backwards and forwards, and it will soon be felt which projects and requires adjusting. The glass mirrors, in order to get a bright reflected light, should be used at considerable obliquity, far beyond the polarizing angle; and a little patience in getting the positions and adjustments will be rewarded with success. The distance from the luminous point to the eye-lens should be several yards, and the best intermediate place for the mirrors can be found by experiment.

Fresnel also invented the obtuse-angled prism to try the same experiment, as ACB in fig. 47. When once obtained, these prisms are very convenient for showing the experiment in a popular way, as they are easily mounted in their place, and are not liable to get out of adjustment like the mirrors. But they require the two plane faces AC, BC to meet sharply up to the angle C, and this requires more care than the working opticians will generally give in the grinding and polishing. The angle ACB should be not more than two or three degrees less than two right angles.

Fig. 47.



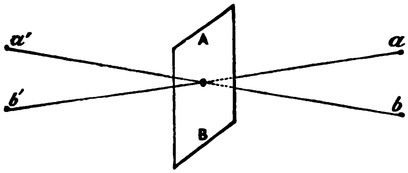
If F be the luminous point, its two images *a* and *b* will be as in the figure, and the interference phenomena are produced as in the last method with mirrors.

These experiments can be tried with lamplight by using a line of light in place of a point of light, and placing the edge where the mirrors meet *accurately parallel* to it; or if the prism is used, the edge in which the faces meet at C must be *accurately parallel* to the line of light. The line of light would be generally the light of an Argand or other good lamp shining between the straight edges of two plates of metal nearly close together.

These experiments furnish the means of measuring the luminiferous intervals for different colours of light, for which we generally put the Greek letter $\lambda$. Suppose P and *c* are the places of like interference, in the last figure, such as the centers of neighbouring dark bars, and we measure accurately with a micrometer the distance P*c*; then if we measure the angle which the distance *ab* subtends at P, this is the angle P*cd* in the triangle P*cd*, and this being known, the side P*d*, which is ($\lambda$) the luminiferous interval, is easily calculated.

To find the angle P*cd* we require only to know the distance of *a* and *b*, and their distance from P. Their distance from each other is obtained by experiment as follows: place a thin plate of metal, as AB (fig. 48), with a small pin-hole in it, half-way between the micrometer and *ab*, measure the distance $a'$ $b'$ of the centers of the beams transmitted through the hole with the micrometer, and this is the distance of *a* and *b* as required. The centers $a'$ and $b'$ of the transmitted beams are well seen in the *diffracted light* furnished by the small hole in AB. The distance of P from *a* and *b* is easily measured with a rule.

Fig. 48.



M. Fresnel found the luminiferous interval for the red light transmitted by the old red glass of stained glass windows to be .0000251 inch.

The author, by a like experiment, found it, for the red of infusion of alkanet root in oil of turpentine, to be .0000266 inch.

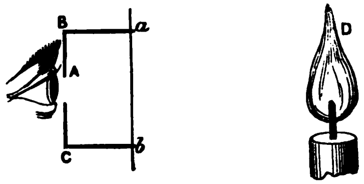
These are the measures inserted in the general table of the values of $\lambda$, which will be found in the discussion of the colours of thin plates further on.

## ON THE DIFFRACTION OF LIGHT.

The experiments in diffraction require a luminous point or line in order to show them well, but they are very easy to perform. The term *diffraction* was first given by Grimaldi*, who has described some cases. Newton described some forms of experiments under the term *inflexion* of light in his 'Opticks.' Dr. Young† undertook the explanation of the fringes or bars at the borders, and within the shadow of narrow bodies, by the doctrine of undulatory interferences, and thus brought that theory again into notice, which has since, by himself and M. Fresnel, been so fully developed, and so generally received by mathematicians.

The simplest way of showing these fringes is as follows: take a strip of card 2 inches long and $\frac{3}{4}$ths of an inch wide, and cut in its center A (fig. 49) a hole $\frac{1}{10}$th of an inch broad, and $\frac{1}{4}$th of an inch long, with the long side of the hole parallel to the length of the card: bend the card twice at right angles at B and C in the figure, and making slits at the ends, stretch a hair of the head across from one to the other, as *ab*. Now looking through the hole A, past the hair towards a flame of a candle D, which should be as distant as possible, and in a dark room, we see coloured fringes on each side of the shadow of the hair, and narrower and less coloured bars inside it.

Fig. 49.



To try the experiments of diffraction accurately so as to be enabled to make measures of distances, &c., a luminous point and a dark room should be used.

To examine the diffracted fringes near the shadow of a narrow body, let F be the luminous point, A the section of the narrow body, such as a needle, L the eye-lens, and E the eye in fig. 50.

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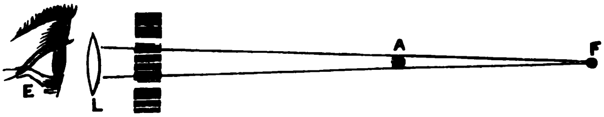
* Physico-Mathesis de Lumine. Bononiæ 1665, and an account of the work, Phil. Trans. 1672.

† Phil. Trans. for 1802, p. 389.

Draw lines from F touching the sides of the body A, then if

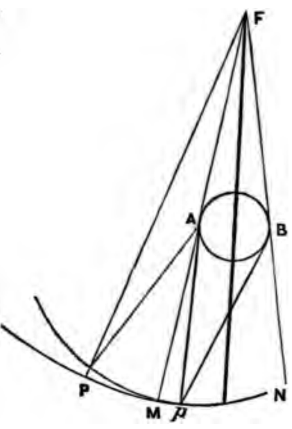
Fig. 50.



these lines be continued onwards, the space between them is called the geometrical shadow of the body A, or the shadow as it would be if the light were unaffected by diffraction on passing the edges of A.

When we examine this shadow with the eye-lens, we see bars or fringes within it and without it, as sketched in the figure. The exterior bars are highly coloured and faint, and only three or four are visible in ordinary white light; their breadths depend on the distances FA and AL only, and become broader as AL is greater. The interior bars are bright and dark alternately, with less colour than the exterior ones, and their number, and consequently their breadths, depend upon the size of the body A, as well as on the distance AL. They are narrower and more numerous as the body (supposed narrow) is broader.

Fig. 51.



Dr. Young's explanation was as follows: let F (in fig. 51) be the luminous point, AB the section of the body, draw FAM, FBN touching the body at A and B, then between M and N is the geometrical shadow. Let P be a point without and $p$ a point within this shadow. Now at P the interference arises from a ray AP reflected at the edge A, with the one, FP, coming direct from F to P, and the distances FA and AP together are greater than FP, so that the reflected ray is retarded behind the direct ray, and the interference depends upon the amount of this retardation. The objection to this view is, that half an interval is required to be considered lost in reflexion at A, since at the boundary of the geometric shadow there is darkness instead of brightness, the two rays having travelled the same distances to that point. This begging half an interval was considered an objection to the undulatory theory, since no reason could be given why it should be this magnitude, and for all colours with their different magnitudes of intervals. With this half interval allowed, the measures of the positions of the fringes in homogeneous light, or that of one colour only, were found by M. Fresnel* to be in accordance with theory within the limits of errors of observation.

The interference at $p$ within the shadow arises from the rays inflected into the shadow at A and B, the two edges of the body. The central bar is *always* a bright one, and the whole are in accordance with the undulatory explanation. Bringing a card up to one side of the body, the bars disappear, showing that they arise from the interference of two pencils.

The light inflected into the shadow is best examined within that of a broad body, when the exterior fringes will be seen, and also the inflected light shading away gradually into darkness within the geometrical shadow. If we consider, with Dr. Young†, the form the luminiferous surface must take, except as to the loss of the half interval, we shall find it such as the curve line PM$p$ in the figure; since the change is from a direct ray FP at P to an inflected ray at $p$, and then gradually to darkness within the shadow, and from this back to rays reflected at A; and thus it forms a continuous but *duplicate* sheet. Now within the geometrical shadow of a *narrow* body the duplicate sheet from one side interferes with the duplicate sheet from the other side, and we might expect different results to those of the interference of single sheets. It appears that the interior fringes should be considered to have been subject to anatropy or inversion, and that the external ones are the normal cases of interference; the phenomena are then in accordance with the experiments with the two mirrors, and the interference cannot be undulatory interference.

M. Fresnel having afterwards adopted another view, it becomes necessary to examine if the inflected and deflected light supposed by Dr. Young does really exist. The edge and back of a razor are often referred to, as affording the same exterior fringes. Now if we place the blade of a sharp razor with a round back in the sun's light, as in fig. 52, we shall, by placing the eye in the different positions and shading it when required, see both inflected, and deflected or reflected light to come from A and B. There is this difference, however, the sharp edge A gives a feeble reflected light compared with the round back B, but it gives an inflected light far stronger and visible much further into the shadow. These in fig. 52 are supposed to be represented by the closeness of the lines drawn to represent the rays.

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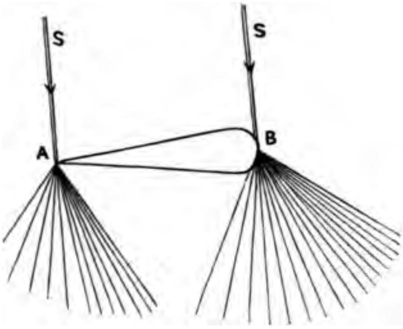
* Annales de Chimie et de Physique for 1815, tome i. p. 239.

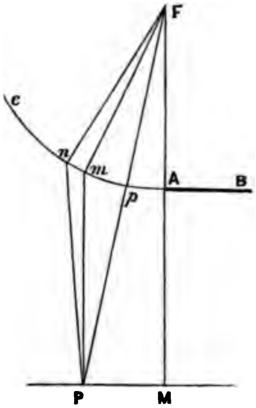
† Philosophical Transactions for 1802, p. 43.

Fig. 52.



Now the existence of these inflected and deflected rays being easily visible, it is clear we have sufficient causes for the interference which we see, without any other theory, and they *cannot be neglected.*

Fig. 53.



M. Fresnel's later method*, which has been generally adopted, was an extension of Huygens's principle, as explained in discussing the law of the ordinary refraction of light. The wave from a luminous origin F, on arriving at an opaque screen AB, being partially interrupted, the portion A*pmnc* being supposed made up of elementary origins as *mn*, the integral effect or sum of the effects of these at a point P was considered to give the intensity of the light at P. This method of solution gives very nearly the same results as Dr. Young's method without begging half an interval. The difference between the solutions being very slight, M. Fresnel states that a re-examination of the experiments showed them nearer to his later than to his former method, which was Dr. Young's.

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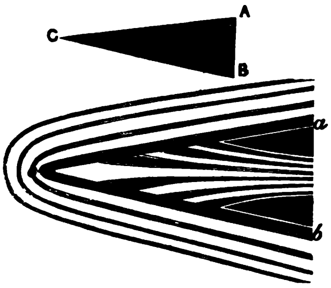
* Annales de Chimie et de Physique for 1819, tome xi. p. 246.

Now this method of considering a wave in any position as made up of the elementary origins of new waves, fails completely to give results in accordance with the experiments in many other cases*.

We must hence conclude that the phenomena of interference must be discussed in the method introduced by Dr. Young, but noting that the normal case gives darkness where the rays have travelled over equal distances, contrary to the undulatory theory of light; and where there is inversion of properties, there is brightness where the rays have travelled over equal distances.

If the opaque body has an angular point, as ACB (fig. 54), of which the geometrical shadow is *acb*, the exterior fringes are seen bending in continuous curves round the point, and the interior bars becoming less numerous and more divergent as we come nearer to the point, the central one being a bright one.

Fig. 54.



If the body is a small *circular* opaque disc, we have the exterior fringes in rings, and the interior ones have a bright spot for center†. To try this experiment, a disc of $\frac{1}{10}$th of an inch diameter or smaller, should be turned in metal, with a moderately sharp and smooth edge, and a smaller base by which it may be cemented to a well-polished sheet of plate-glass. By this means, when the disc is placed in the light diverging from the luminous point, it will appear as if suspended in the air, and the diffraction will be seen complete.

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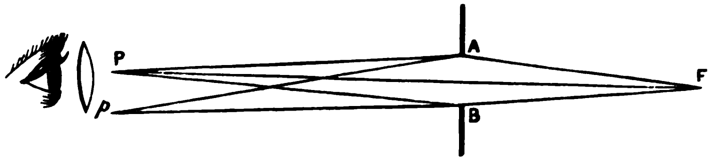
* Compare Mr. Airy's tract 'On the Undulatory Theory of Optics,' articles 78 and 25, with Newton's experiment, 'Opticks,' 3rd edition, p. 304; or Herschel's 'Treatise on Light,' art. 742. See the Rev. S. Earnshaw's paper "On a triangular aperture before the Object-glass of a Telescope," Cambridge Phil. Trans. vol. vi. p. 431; papers by the author and others in the 'Philosophical Magazine' for October and December 1840, January and August 1841. Mr. Airy's paper "On the interference of Light near a Caustic," Camb. Phil. Trans. vol. vi. p. 379, for 1838; and the author's paper on the same subject in the 'Philosophical Magazine' for May 1855.

† See Philosophical Magazine for August 1841, p. 151.

When light passes through small apertures, after diverging from a luminous point, we have interference effects from the direct, the inflected, and the deflected lights.

When the aperture is a long and narrow parallelogram between metallic edges, if we examine with an eye-lens *very near* it, the light passing through the aperture, we see the diffracted fringes as above discussed, and the light inflected into the shadow shading away to darkness on each side; but when the aperture is narrow compared with the *distance* of the eye-lens, we have the rays diffracted at the edges interfering with each other as well as with the direct light.

Fig. 55.

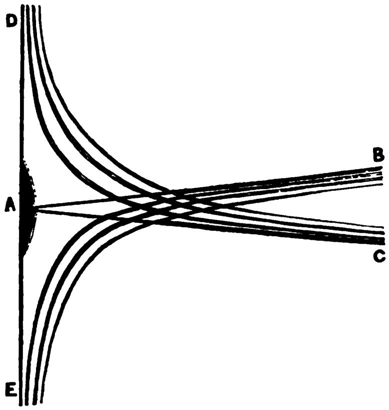


Let F (in fig. 55) be the luminous point; A and B the edges of the aperture, which may be cut with a penknife in a piece of tinfoil attached to a plate of glass, and let P be the center of the transmitted beam, which is examined with an eye-glass, as in the figure. Then at some distances of P from A and B we have a bright bar in the center, at others a dark bar, and at others again variously coloured ones; these all depending upon the retardations of the rays FA, AP or FB, BP behind the direct ray FP. At other places, as *p*, the rays diffracted from A and B interfere, and produce great varieties of beautiful effects. When the distance of the eye-lens from A and B is exceedingly great compared with the width of the aperture, we have finally a bright central bar ruddy on its edges, and highly coloured bars symmetrical on each side of it.

If the edges, instead of being parallel, meet at an angle, as in Newton's experiment of two knives with their points stuck into a piece of wood, and their edges meeting at a small angle, say a little less than two degrees, we have the light passing through this angular aperture, exhibiting the whole of the above phenomena at the same distance of the eye-lens, arising from the variable distance of the edges.

If AB, AC (in fig. 56) are the boundaries of the geometrical shadows of the knife-edges, then the fringes take the forms of two sets of hyperbolas as in the figure, with asymptotes, the lines AB, AC and the line DAE perpendicular to a line which would bisect the angle BAC.

Fig. 56.



We see that there is not any break in the continuity of the interference curves though the different parts are formed so differently. The crossing of the hyperbolas shows how the central bar at moderate distances exhibited such variety of brightness and colour when the aperture was a narrow parallelogram.

The bright part near the angle A shows how at very great relative distances we found a bright central bar and coloured ones on each side of it.

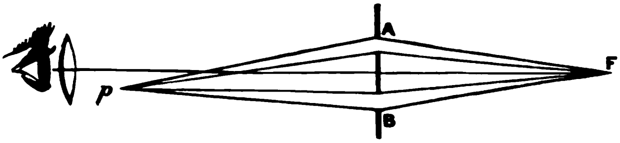
The properties of the hyperbola referred to its asymptotes, enable us to compare the breadths of the fringes with the distance of the knife-edges at given places. An approximation for points near the angle A, has been given in the undulatory theory as the strict rule, for the form of the fringes.

When the aperture is a *small circular hole*, such as a pin-hole in a thin plate of metal, as a piece of lead beaten thin, or tinfoil, the appearances in the transmitted light are very interesting, consisting of rings and a central spot continually changing in character and colour with change of distance of the eye-lens. Where that distance is very great, the center becomes permanently a bright one. The changes are analogous to those of the two last cases.

When there are two apertures near together, whether parallelograms or circles, we have besides the interference of the separate apertures, that of the diffracted light of one with the diffracted light of the other aperture.

In fig. 57, let A and B be the two apertures, and *p* a point

Fig. 57.



where lights diffracted at each of the apertures will meet, then we have a new interference superadded to that for the separate apertures themselves.

It was by an experiment of this form that MM. Arago and Fresnel proved the properties of polarized beams with regard to interference, by placing plates of tourmaline, cut from the same plate, before the apertures A and B; it was then found that if the plates were in similar positions, the interference occurred as in ordinary light, but if they were set at right angles there was no visible interference of the two beams. This showed that two beams of light, polarized in planes at right angles to each other, did not interfere so as to produce change of brightness. Like experiments were tried by placing bundles of plates of mica before the apertures. A reference to these experiments will be found in the chapter on Polarization.

When plates with many and varied apertures are used, such as the perforated zinc used for window-blinds, the play of colours, and the varied forms of the interference curves, are frequently magnificent.

Lord Brougham has lately investigated some interesting cases where the light diffracted by one edge of an opaque body falls upon another edge and is diffracted again. The phenomena then exhibited merit the attention of those studying the higher branches of Physical Optics. See tome xxv. de l’Académie des Sciences.

Mr. Barton, by ruling, in a machine constructed for the purpose, very fine lines exceedingly close together upon surfaces of polished steel with a diamond, produced what he termed *iris ornaments*, giving splendid rainbow phenomena. He also stamped from steel dies the same kind of systems of fine lines in various patterns upon gilt buttons. These articles, neglected by the vanity of this world, are become rare and valuable philosophical apparatus.

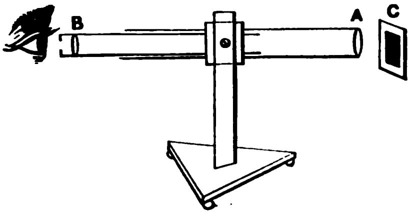
An approximation to the effects of Mr. Barton's iris buttons are seen when we look through feathers of birds towards a luminous point.

Mother-of-pearl owes its colours to the same order of diffraction from systems of fine lines close together. Those on mother-of-pearl may be copied upon sealing-wax by pressure when it is soft, and it will then exhibit the interference colours.

We are indebted to M. Fraunhofer for the discovery* of a class of diffraction experiments, which are amongst the most beautiful sights known, as well as important in their theoretical bearing. In these experiments various forms and arrangements of apertures are placed before the object-glass of a telescope, which is directed towards a luminous point.

A very simple and easily made telescope is sufficient to exhibit these beautiful interference phenomena. A common spectacle lens of two or three feet focus, and an eye-lens of one or two inches focus, mounted in tubes of pasted paper, are quite sufficient, whilst micrometer measures are not intended to be taken. The length of the outer tube carrying the object-glass should be nearly the focal length of that glass, and the length of the inner one ¾ths of it. This latter carrying the eye-glass, can then be drawn out so as to view distinctly a luminous point which is moderately near. The lenses should be set as perpendicular to the axes of the tubes as possible, and the whole may be mounted conveniently on a wooden stand, as in fig. 58.

Fig. 58.



Let A be the object-glass, B the eye-glass, with an eye-hole a little less than its focus from it at the eye-end of the telescope.

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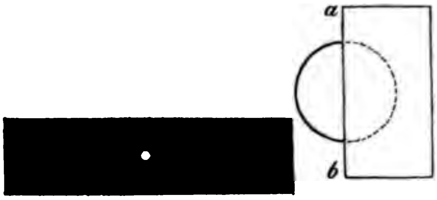
* "Neue Modifikation des Lichtes," Denkschriften der Akademie zu München, für das Jahr 1821.

Let the eye-tube be drawn out until the image of the distant luminous point is seen in the telescope distinctly, then place the support of the apertures at C, between A and the luminous point, and the interference phenomena will be seen in the telescope at the focus of the eye-glass.

On account of the magnifying power of the telescope the luminous point should be small, and as distant as can be conveniently used. If only short distances such as four to six yards can be employed, the object-glass should be only of one to one and a half foot focus. It will be found convenient to have the support for the apertures attached to the object end of the telescope.

The first experiment to be tried is to place a straight edge of a knife or of tinfoil across the object-glass, and covering part of it, as *ab* (fig. 59). The image of the luminous point which appeared as a bright spot *f*, before the straight edge was placed before the object-glass, now appears with a bright bar *cd* through it, as in the figure. It is easy to see how the bright bar arises. Referring to fig. 51, we see that the luminiferous surface, where altered by diffraction, after passing the edge *ab* (fig. 59), is unaffected in the direction parallel to the edge, but will be formed of arcs nearly circular in the direction perpendicular to it. Now in the first direction the object-glass brings the rays to a focus, but in the second it has no effect, since the diffracted rays originate at points nearly at its surface, and thus these diffracted rays are refracted into a straight line by the object-glass.

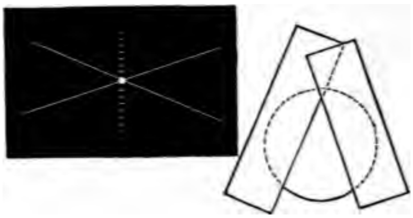
Fig. 59.



If we place two straight opaque edges inclined at a small angle in front of the object-glass, as in fig. 60, then in the field of view we have a bright point, with two rays through it as in the figure, each perpendicular to one of the edges, and faint bars in the obtuse angle as in the figure, which arise from the portions of the luminiferous surfaces, which give the parts of the hyperbolic fringes near the angle of fig. 56.

When the aperture is a small equilateral triangle, as in fig. 61, cut in tinfoil, we have a beautiful six-rayed star, as in the figure. The formation of the rays is evidently the same for each as for the single edge, except near the angles, where an effect as in the last case occurs.

Fig. 60.



There are changes, however, attending the change of size of the aperture. With an object-glass of 17 inches focus, when the sides of the triangle were ¾ths of an inch, the rays came up to the central spot; but when the sides did not exceed ¼th of an inch, the rays were barred across, and separated from the central spot. When the eye-lens was put out of focus on either side, the six rays were found to change continuously into hyperbolic curves and series of bars alternately. The appearances on the opposite parts from the center of the three straight lines being interchanged on passing through the focus, these results arise from the hyperbolic curves of fig. 56, modified by the object-glass.

Fig. 61.

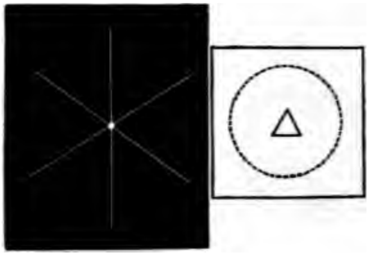
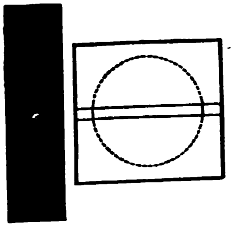


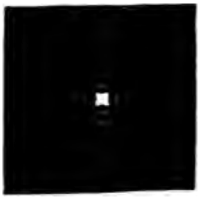
Fig. 62.



When the aperture is a narrow slit or long parallelogram, as in fig. 62, of $\frac{1}{30}$th of an inch broad, the central image *f* is elongated, and the line broken up into coloured spectra, as in the figure, by the interference of the light diffracted from one edge with that from the other.

As the slit is *wider* the spectra are *closer*.

Fig. 63.



When two of these slits are crossed at right angles, we get a *small square aperture*, which gives a four-rayed star, and the spectra are broader, as in the next case.

When a square aperture was used of about ¼th of an inch in the sides, the appearance was a square-shaped central spot, with rounded corners and four barred rays, as in fig. 63.

When out of focus the appearance was that of nine spots, all coloured except the central one, and many other small ones in square arrangement, as in fig. 64.

With a *square* aperture half an inch in the sides, the four-rayed star was again seen, as in fig. 65, with the transverse bars very close and narrow. Out of focus on either side, the four-sided center showed the origin of the nine images, with fainter ones more distant, as in fig. 64. The appearance in this case was like fig. 66, with the rays striped longitudinally.

Fig. 64.

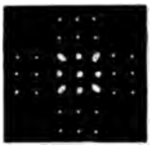


Fig. 65.

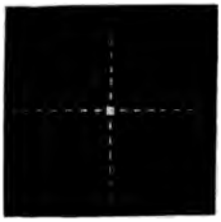
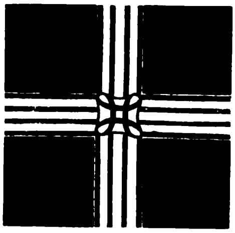


Fig. 66.



These are the ordinary diffraction phenomena modified by the object-glass, as considered in the first experiment.

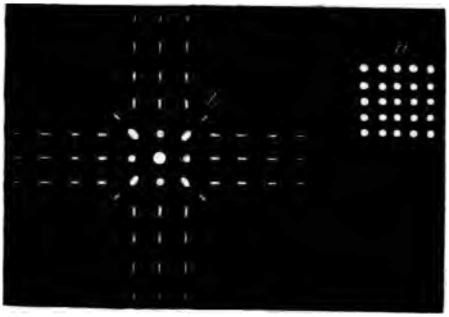
A small circular aperture gives an enlarged central spot as an image of the luminous point, towards which the telescope is directed, with coloured rings around it. The central spot becomes smaller, and the rings closer as the aperture is enlarged. This experiment explains the origin of the spurious discs of the fixed stars which are seen in telescopes, and shows how they become larger as the circular aperture of the object-glass is diminished.

When a number of small apertures in regular positions are used, varied and very beautiful appearances are produced.

A series of small circular holes in perforated zinc, in square arrangement like the figure 67, at *a*, gave an appearance like that at *b* in the common focus of the object-glass and eye-glass.

The central spot of the nine larger ones was white, being the ordinary image of the luminous point, but the others were splendid prismatic spectra.

Fig. 67.



When wire-gauze, such as is used by corn-millers, was placed before the object-glass, spectra similar to the above were formed; and when it was coarse, there were twenty-one brilliant spots, with four fainter ones in the angles of the square.

It is to these appearances that Sir John Herschel refers, when he calls them "the most magnificent phenomena in optics."

When a plate of perforated zinc, with larger circular holes at regular distances surrounded each by eight small holes, was placed before the object-glass, the appearance was very interesting. It consisted of a central bright star, with small coloured spectra close around it, and then a broad faint coloured ring studded with stellar points.

There are many other arrangements of combined apertures which give very beautiful appearances.

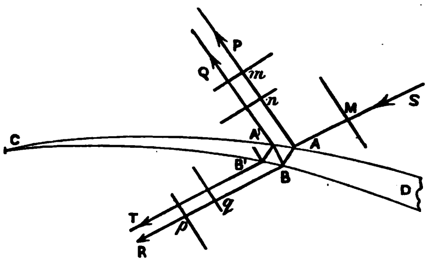
Fraunhofer tried many important experiments with *gratings* placed before the object-glass, which consisted of fine lines drawn with a diamond upon glass very close together (200 to 1000 in an inch give very distinct spectra), upon gold-leaf on glass, and on grease upon glass. These gave spectra in which the colours were separated so accurately as to show the fixed lines, and being independent of the dispersive power of glass or other medium, formed into a prism to show the pure solar spectrum; this diffraction spectrum has been called the *normal spectrum.*

## ON THE INTERFERENCE COLOURS OF THIN PLATES.

The colours of thin films present themselves very frequently to our notice in ordinary daylight. The soap-bubble, thin films of varnish, tarnish on metallic surfaces, the decaying surface of glass which has lain in the earth, cracks in transparent substances, and numerous other cases exhibit these colours in ordinary daylight. In these cases every luminiferous surface which is reflected in two by the two surfaces of the thin film, produces like interference, and the phenomena are visible at once.

In all these cases there are two reflecting surfaces near together, and the phenomena are called generally the colours of thin plates. The easiest way of forming a permanent thin plate for experiment, is to press two surfaces of glass together, and thus obtain a thin plate of air between two reflecting surfaces of glass. When wiped very clean, even thick pieces of plate-glass can be bent by the pressure of the fingers so as to show these interference colours. When we want the bands of colour of considerable breadth, this is often the best way to obtain them; but two pieces of window-glass taken at random are seldom so flat everywhere, that, on cleaning them well, they do not even with slight pressure exhibit colours in irregular rings in some parts.

Fig. 68.



Let CADB be a transparent film, such as part of a thin blown bulb of glass, or a soap-bubble; SA a ray of light incident at A, refracted in AB, and finally emergent in BR. Now there will be rays reflected as AP from the first surface at A, and as BA′ from the second surface at B. The latter falling at A′ on the upper surface, will be partly emergent in A′Q, and partly reflected in A′B′. This latter will be partly emergent in B″T, and partly reflected again. Now if we suppose a luminiferous surface at M to be perpendicular to SA, the incident ray, we shall have the corresponding luminiferous surfaces after the reflexions perpendicular to the rays respectively; but the one at *n* perpendicular to A′Q will be retarded behind the corresponding one at *m* perpendicular to AP by the distance *m n*, which equals AB plus BA′ within the film, or AB plus A′B multiplied by the refractive index of the film in air; and originating from a common luminiferous surface M, they are in a fit state to interfere.

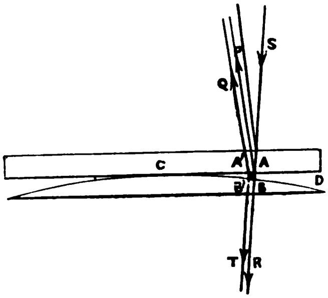
The luminiferous surface at *p*, perpendicular to the emergent ray BR, is followed by another at *q*, which is perpendicular to the ray twice reflected, namely at B and A′, which emerges at B′, and the retardation of the latter equals BA′ plus A′B′ in the film, or the same as the reflected rays if we consider the surfaces of the film parallel through the small space AA′B′B. This retardation in the medium is to be converted, as before, into the corresponding one in air.

Now the two reflected rays do not differ greatly in intensity, which is for each about $\frac{1}{30}$th that of the incident light for glass, and therefore their interference produces blackness where they destroy each other. The transmitted light has the principal beam of little less intensity than the incident beam, having lost about $\frac{1}{30}$th part by reflexion at each of the points A and B; but the intensity of the twice reflected beam, which interferes with it, is about $\frac{1}{30}$th of $\frac{1}{30}$th, or $\frac{1}{900}$th of that of the incident beam; hence the difference of the intensities of the bright and dark bands is never like what occurs in the reflected beams. It is, however, much greater in red light than we should have expected, and differs for different colours of the spectrum, being least in violet light. This is contrary to the undulatory theory, and will be referred to again.

When the thin plate of air is formed between two spherical surfaces of glass, as when two lenses are pressed together, or when one of the surfaces is plane, the interference curves become circles, and the phenomena are called *Newton's reflected or transmitted rings* respectively.

Let the figure 69 represent a plate of glass laid upon a convex

Fig. 69.



lens; let C be the point of contact, and CA′ADBB′ the thin plate of air, from the reflexions at the surfaces of which the interference arises in the beams emergent from the glass.

Now the retardations from which the interferences in the reflected and transmitted lights arise, will be similar to the former case, and will be the same at the same distance from C in all directions around it, and hence the interference bands will be now circles with center C. If the light falls nearly perpendicularly on the surface, the retardation of one ray behind the other in both systems is twice the thickness of the plate of air at any given point, and this can be easily calculated when we know the radius of the spherical surface. We know by geometry that the thickness of the plate of air is proportional to the square of the distance from C, and for this reason the rings are broadest near the center, and become rapidly narrower as they are further away. The same interference occurring when the retardation is $\lambda$, or $2\lambda$, or $3\lambda$, &c.; and also when it is $\frac{\lambda}{2}$, or $\frac{3\lambda}{2}$, or $\frac{5\lambda}{2}$, &c., we have the radii of the bright and dark rings proportional, one of them to the square roots of the series of numbers 1, 2, 3, &c., and the other to the square roots of the series of odd numbers 1, 3, 5, 7, &c.

The interference depending on the relation which the retardation bears to the interval $\lambda$ between successive luminiferous surfaces for each colour, the bright and dark rings have different radii for the different colours of the solar spectrum, and hence near the center the rings are coloured on their edges, blue on the inner edge, and red on the outer edge; but after a few alternations, the colours become so mixed in ordinary daylight as not to be discernible beyond eight or nine rings in number. If, however, we employ homogeneous light, or that of one colour only, such as the light from a spirit of wine lamp with a salted wick, we see great numbers of bright and dark rings in the reflected light, which only becomes of apparently uniform intensity by their being very close together. By placing before the eye pieces of red, green, or blue glass, although the light they transmit is not quite purely of one colour, yet great numbers of rings are visible; and it is also easily seen that in red light they are larger than in green, and in green they are larger than in blue light. When measures of the rings of different colours are required, a pure solar spectrum should be used; and then, when the diameter of a given ring (say the sixth where the thickness of the plate of air is six times that where the first occurs) is measured, we have the means of calculating the value of the luminiferous interval ($\lambda$), since the radius of the spherical surface is supposed to be known to great accuracy. By many measures Newton concluded that (with citrine yellow light, as in observation 16) the distance between the reflecting surfaces, or the thickness of the air where the darkest part of the *first* dark ring occurred, measuring from a black center*, was $\frac{1}{89000}$th part of an inch. Now the retardation is the double of this, and is the value of $\lambda$, since it is the retardation in going from the black center to the first black ring, or $\frac{1}{44500}$th of an inch.

With this for basis and the proportions for other colours from analogy with the musical notes in an octave†, which Newton gives, the three first columns of the following table were computed by Dr. Young‡, and still remain the numerical basis of Physical Optics, until better methods of measuring the intervals ($\lambda$) shall have been established.

It will be noted in the table, that the measures for the red rays are not more different than might be expected from different methods of experiments. M. Fresnel and the author nevertheless concluded that the numbers of Dr. Young were rather too small. The difference for the violet rays, as determined by M. Fraunhofer, is, however, very great; and it is a desideratum of Physical Optics, that a correct table of the values of $\lambda$ should be obtained by a fresh comparison of Fraunhofer's results with those given by other methods of experiment.

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* Newton's 'Opticks,' 3rd edition, p. 178.

† Newton's 'Opticks,' p. 186.

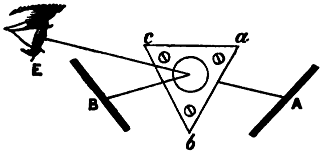
‡ Phil. Trans. for 1802, p. 39.

| Colours. | Length of an interval ($\lambda$) in decimals of an inch in air. | Number of intervals in an inch, or $\frac{1}{\lambda}$. | Fraunhofer's results from diffraction for the different fixed lines of the solar spectrum. | | Fresnel's result for orange-red glass from diffraction and the two mirrors. | The author's result for red of alkanet root in oil of turpentine with the two mirrors. |
|---|---|---|---|---|---|---|
| Extreme | ·0000266 | 37640 | $\lambda_B$ | ·00002708 | | |
| Red | ·0000256 | 39180 | $\lambda_C$ | ·00002581 | ............ | ·0000266 |
| Intermediate | ·0000246 | 40720 | ...... | ............... | ·0000251 | |
| Orange | ·0000240 | 41610 | $\lambda_D$ | ·00002318 | | |
| Intermediate | ·0000235 | 42510 | | | | |
| Yellow | ·0000227 | 44000 | | | | |
| Intermediate | ·0000219 | 45600 | | | | |
| Green | ·0000211 | 47460 | $\lambda_E$ | ·00002073 | | |
| Intermediate | ·0000203 | 49320 | | | | |
| Blue | ·0000196 | 51110 | $\lambda_F$ | ·00001912 | | |
| Intermediate | ·0000189 | 52910 | | | | |
| Indigo | ·0000185 | 54070 | $\lambda_G$ | ·00001691 | | |
| Intermediate | ·0000181 | 55240 | | | | |
| Violet | ·0000174 | 57490 | $\lambda_H$ | ·00001560 | | |
| Extreme | ·0000167 | 59750 | | | | |

The faint rings seen in the transmitted light, we found arose from the interference between the directly transmitted beam and that which had been twice reflected internally, but the retardation was the same at any point as for the reflected rings; this would lead us to expect the *bright* rings in the transmitted light to correspond in diameter with the *bright* ones in the reflected set of rings, and the *dark* ones of one set with those of the other set. Such, however, is not the case, for the diameters of the *bright* rings in the transmitted light equal those of the *dark* rings in the reflected light, and the diameters of the *dark* ones of the former equal those of the *bright* ones of the latter. It was found by M. Arago that the two sets, if superposed, produced a uniform white light; which, if not accurately, can at any rate be shown to be approximately true, in a simple manner, as follows:—

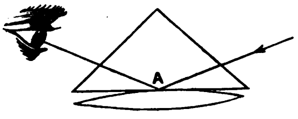
Place two upright pieces of card-board, as A and B, before a window, and equally inclined to the light, so as to be equally illuminated. Let *abc* be the apparatus producing Newton's rings, consisting of two triangular pieces of wood of $\frac{1}{8}$th of an inch thick, having circular apertures through their centers one inch in diameter. A spectacle lens of long focus, and a piece of flat glass being, when well cleaned, placed between the two pieces of wood, they are to be pressed together by three small screws in the angles, as in the figure *abc*, when Newton's rings of sufficient size for the experiment will be visible. If now the eye be placed at E so as to see the transmitted rings by light coming from A, and the reflected rings by an equal light coming from B, it will be found that they obliterate each other, and leave a uniform light.

Fig. 70.



From these facts, we conclude that one of the sets of rings is subject to anatropy, and we have to examine the circumstances in order to determine which must be considered the normal interference. Now the reflected rings are formed by rays reflected, one internally, and the other externally; and hence we may expect them to be subject to anatropy rather than the transmitted rings. Again, if the reflected rings are formed by pressing a lens to the base of a prism (or thick plano-convex lens), as in the figure 71, and we look very obliquely into the prism towards the point of contact, so that the light is generally totally reflected at the base of the prism, we see that the rings around the point of contact A, which were visible whilst looking more directly above A, have disappeared; but that the black spot at the center, and the grey light round it, remain, and have increased in size. The total reflexion commences only at the first bright ring, and the separation between the surfaces, as far as reflexion and interference are concerned, commence therefore only at the place of the first bright reflected ring. This corresponds with the first dark ring in the transmitted light, and as the normal interference we have again rays which have travelled over equal distances producing darkness.

Fig. 71.

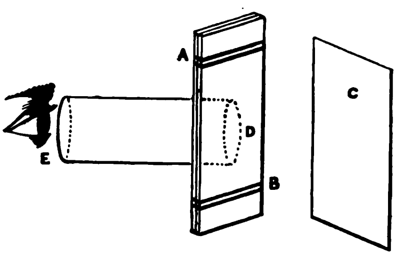


As Newton's measures, from which he calculated the distance between the surfaces of his lenses, were made on the fifth and sixth reflected rings, they will be affected by the rings being formed with a black center; and we need not be surprised at the difference found for the values of the intervals in the table by diffraction, and the two mirrors slightly inclined.

When the reflected rings are viewed obliquely, they are seen to increase in diameter with the obliquity, and Newton has given a rule for the change, but we see that he employed black centered rings.

It was stated that the transmitted rings, though faint, yet exhibited in homogeneous red light greater difference between the maxima and minima intensities than we should have expected. This is one of the most important experiments on theoretical grounds in Physical Optics, for it is the one which especially indicates how interfering lights of different intensities are to be compounded, and it may be called the fundamental experiment for intensities.

Fig. 72.

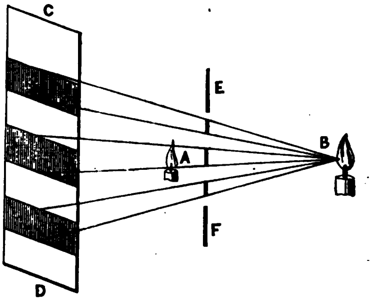


Let AB represent two slips of plate-glass pressed or bound together so as to show broad bands of bright colour from the interference of the light reflected at the surfaces of the thin plate of air between them. To prevent obliteration of the transmitted rings arising from the reflected ones, let them be examined by looking through a tube blackened in the inside, as DE; and an eye-lens, except for short-sighted eyes, in the tube is an advantage. Now turning the apparatus towards a strong light, the transmitted rings will be seen. If we place a piece of red glass, as C, before the rings, the difference of brightness of the bright and dark bands will be found very great; if we put a piece of green glass at C, the difference will be less considerable than with the red glass; and if we use a piece of blue glass the difference will be found to be small. It is clear that the true interference rule for calculating the intensities must involve the luminiferous interval λ, so that a weak interfering light in red shall produce a much greater result than if it were of green or blue.

Now the undulatory theory being a purely mechanical theory, it was easy to find the relative intensities for these transmitted bands. According to the formula investigated for the intensities*, the ratio of the brightness in a dark band to that in a bright one for all colours is 1 to 1.1538, or as 1 to 1$\frac{1}{7}$th nearly, taking the reflected light to be $\frac{1}{30}$th that of the incident light: and according to Mr. Airy†, taking into account all the reflexions, and using the undulatory value of the reflexion, the ratio is 1 to 1.173. These can be easily examined by photometry.

It is shown both by theory and experiment that the intensity of light falling upon a screen from a luminous origin is inversely proportional to the square of the distance; that is, if the luminous origin be at twice the distance, it gives only one-fourth the illumination; and if at three times the distance, it gives only one-ninth the illumination, which it did at first distance; and similarly for other distances.

Fig. 73.



Now suppose two candles to be burning with equal intensities, which can be easily proved by seeing that they cast equally dark shadows of a narrow body, such as a common black lead pencil, upon a screen when at equal distances. Let one of them be placed at A in figure 73, and the other at B, so that its distance from the screen CD is 2.66 times that of A, and its light at the screen is then one-seventh that of A. Now if the light from B be partially interrupted by a screen EF, with long narrow apertures cut in it, then the places where both lights fall will have an intensity 1$\frac{1}{7}$th that of the parts where the light of A only falls upon it. It will be found that this is far below the proportion of the bright and dark transmitted bands when seen in blue light, which is about 1 to 1.5, but very far from it when seen in green and red light. Again, take a rhomb of calc-spar, and cover over its first surface, except a narrow strip of such breadth that the two images of it overlap. Turning the crystal towards ordinary light, the two refracted beams will be of equal intensity, and where they overlap will be of double intensity; comparing these with Newton's transmitted rings, it will be found to represent the ratio approximately of the bright and dark bands seen in green light, that ratio being 1 to 2.5. On examining these rings in red light, it will be found that the difference of the intensities is very much greater still. By a modification of the experiment figured above, with both the lights shining through the apertures in the perforated screen, and their illuminations on CD being in contact to form bars, then when their distances were such that the intensities had the ratio 1 to 3.5, the interference bands in red light were found to be very nearly represented.

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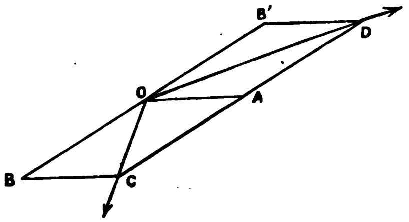
* Herschel's 'Treatise on Light,' art. 662.

† Tract 'On the Undulatory Theory,' art. 67.

In order to explain these phenomena, it is necessary to take the intensity of light as represented by an exponential function of a base, or that the intensity equals this base raised to the power λ multiplied by a constant. In interfering beams the bases are to be compounded by the parallelogram (fig. 8) in the same manner as velocities, and the angle between the sides is half an interval minus the retardation expressed as a circular arc, when the luminiferous interval λ is represented by the whole circumference.

Fig. 74.



In the figure 74, let OA and OB represent the bases of the interfering lights, and let the angle AOB bear to four right angles the ratio which $\frac{\lambda}{2}$ minus the retardation of one behind the other bears to λ; then the diagonal OC represents the base of the interference beam, and its brightness or intensity equals this base raised to the power, λ multiplied by the constant. With the numbers for λ in the table the constant is about 150000*. When the interference is subject to anatropy, the interference base is the diagonal OD of the parallelogram on OB′ (which equals and is opposite to OB) and OA; or it is the diagonal joining A and B in the first parallelogram. The values of these are easily applied mathematically, and the results are in complete accordance with experiments, both for the interference of polarized and unpolarized light.

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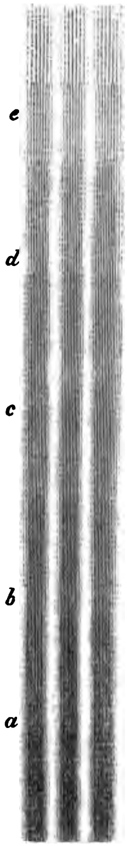
* The magnitudes of λ would be the indices if the unit of measure were the 150000th part of an inch.

Fig. 75.



The measures for green and red light were first obtained by comparative photometry*, and after many years, on examining the transmitted rings in the blue light through a solution of ammoniuret of copper, the author saw, about the year 1845, the importance of the experiments for determining the true interference formulæ. To re-examine the first measures, and also to obtain measures for violet light, the following method was used. A set of stripes upon drawing-paper, like the figure 75†, were made with a hard camel's-hair brush, and fine powder of black lead, shading from small differences at one end of the paper to great differences of light and darkness at the other. Newton's transmitted rings were viewed in different parts of a tolerably pure solar spectrum, thrown upon paper in a dark room, and compared with the appearance of the stripes, like figure 75, in the same colour.

With the assistance of two persons accustomed to scientific experiments, the author concluded the rings in the middle red to be represented by the stripes about *b*, though one of the assistants thought *a* nearer, perhaps from using a more extreme red. In the yellow light it appeared they were represented by the part about *c*, in the green by the part about *d*, and in the violet light by the part about *e*.

Finding the ratio of the intensities by photometry in the method just described of these various parts of the stripes, the values were found to be for *e* in the violet light near the indigo 1 to 1.56; for *d* in the green 1 to 2.4; for green yellow between *d* and *c* 1 to 2.56; and for red between *b* and *a* the ratio was found to be 1 to 3.61, in accordance with the other method.

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* Phil. Mag. for September 1832, p. 177.

† It must be remembered that in printing from a wood engraving the darkness will vary in different copies, and fig. 75 must be considered only as an illustration of the method followed.

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When a lens is pressed upon a polished surface of metal, the reflected rings are seen very bright, but the reflexion from the metal being so much stronger than that from glass, the dark rings are not absolutely black. When the rings were formed by two surfaces of glass, it was seen from the experiment with the prism that the black center arose from the surfaces being in optical contact, and leaving no break of continuity in the substance of the glass. When the rings are formed upon metal the center is not absolutely black under any pressure, and when seen in the totally reflected light changes its size, becoming smaller at greater obliquities.

When the rings are formed between surfaces of glass, if the reflected rings are viewed obliquely with a tourmaline or other analyzer, having its plane of polarization at right angles to the plane of reflexion; then, when the angle of reflexion is the polarizing angle for glass, the rings disappear, since the light polarized in the plane of reflexion, which is reflected by the glass, is not transmitted by the analyzer.

When the lower surface is metallic, the rings in a similar experiment disappear at the polarizing angle for glass, and the metallic reflexion is only visible.

When the lower surface is diamond, glass of antimony, or other high refracting substance, and the reflected rings are examined obliquely with the analyzer, the changes from a dark to a bright center, and changes in the diameters of the rings between the polarizing angle for glass, and that for the high refracting substance, are very interesting, and may, when more critically examined than they have been hitherto, lead to important considerations of the nature of the reflecting surfaces, which bound the thin plate of air. When the lower surface is metallic, there are phenomena of like import when similarly examined.

As large surfaces of diamond are not easily met with, it is well to know that glass of antimony, which may be purchased at the druggists' shops, can be ground and polished like speculum metal*, with fine red oxide of iron for polishing powder. Its refractive index is 2.1, whilst that of diamond is about 2.5, and from its dark colour the glass of antimony has the advantage of giving no visible reflexion at its further surface.

When water is applied at the edges of the glasses forming Newton's rings, it passes to the place where the separation of the surfaces is the least by capillary attraction, and as it comes to the place of the rings they are seen to contract in diameter. By again measuring the diameters of the rings, Newton found that the distance between the surfaces for a given ring† was diminished to three-fourths of the original distance; or it was the original distance divided by the refractive index for water. This experiment Dr. Young saw confirmed Huygens's view, that light moves slower in refracting media, as was stated in the introductory chapter. The value of the interval λ within a dense medium is, hence, its value in a vacuum divided by the refractive index for the medium.

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* Phil. Mag. for January 1834, p. 6.

† Newton's 'Opticks,' p. 182.

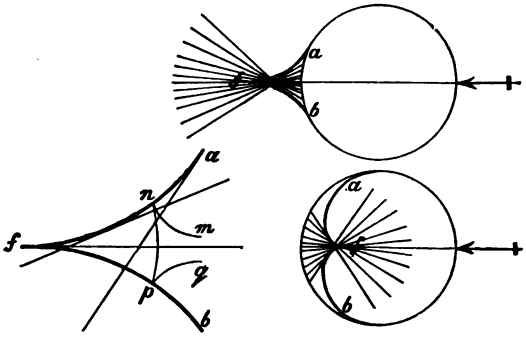
## ON THE INTERFERENCE NEAR A CAUSTIC.

In the cases of interference which have been hitherto considered, the rays having come from a common origin, one of them has been retarded behind the other, and hence the interference; or each single luminiferous surface of the original light has furnished two surfaces which interfere, because one has been retarded behind the other. In certain cases which we have now to examine, the interference must be considered as arising from a single surface redoubled upon itself. Huygens, in the work before referred to, shows the form which the luminiferous surfaces would take after reflexion and refraction; but the interference, when they were redoubled in this manner near a caustic, had never been considered until the author discovered it experimentally whilst examining in 1833 the circle of aberration of a small spherical mirror for a reflecting microscope.

By placing a small globule of mercury in one focus of the mirror, and allowing the sun to shine upon it, a minute but brilliant luminous point was thus formed as the image of the sun given by the globule; then the image of this luminous point formed by the spherical mirror being affected with aberration, the luminiferous surfaces interfered, and formed brilliant and black rings coloured on their edges. On account of the brightness of the light from such a luminous point, and the perfect blackness of the black rings, this is a very splendid though simple phenomenon. The author in 1835 found that the rainbow belonged to the same class of interferences near a caustic, and indeed its explanation is inaccurate without the consideration of interference by the reduplication of the luminiferous surface near the caustic, which is formed by the rain-drop.

A caustic or burning curve formed by refraction, as *afb* in the upper figure, and by reflexion in the lower one of figure 76, can be easily seen experimentally. The first will be seen when a phial of water is placed on a sheet of white paper in the sun's light, and the second when a cup of milk is placed in the sun's light, and in many other easy methods. The caustic curves *afb* in the three figures are formed by the meeting and intersections of the rays of light, which have been refracted or reflected respectively. Now it is shown that the luminiferous surface at

Fig. 76.



each point is perpendicular to the ray, as in fig. 10, and when such a surface is within the branches of the caustic *af*, *bf* in the third figure, it takes the form *mnpq* with cusps or points of regression at *n* and *p*[*]. Now the branches of the luminiferous curves near *n* and *p*, being in contact at those points, and separated by small intervals near them, are in a fit state for interference. The outer ring of the series seen with the spherical mirror and globule of mercury is not brightest at the outer edge as the undulatory theory requires, since the interfering rays at *n* and *p* have travelled over equal distances; but it shades away from its maximum brightness to darkness at the outer edge, in accordance with other phenomena, and we have again *dark interference* where the luminiferous surfaces *have travelled over equal spaces.*

Let A (figure 77) represent the section of a concave spherical mirror, say of one inch focus, and of large aperture compared with its focal length. Let *d* represent a globule of mercury at the extremity of a pin which has been wetted with gum water. Then the sun's light coming in the direction S*d* will form a minute image of the sun in the globule, from which the reflected light will diverge, and fall on the mirror A. Now it is known from geometrical optics, that the rays from the mirror A are not brought accurately to a focus again at *f*, when it is of large size

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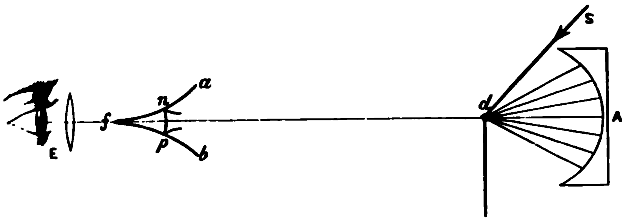
[*] If a thread were stretched along *af*, and then cut at *n*, the extremities, whilst unwrapping, but kept stretched, would describe the arcs *mn* and the half of *np*.

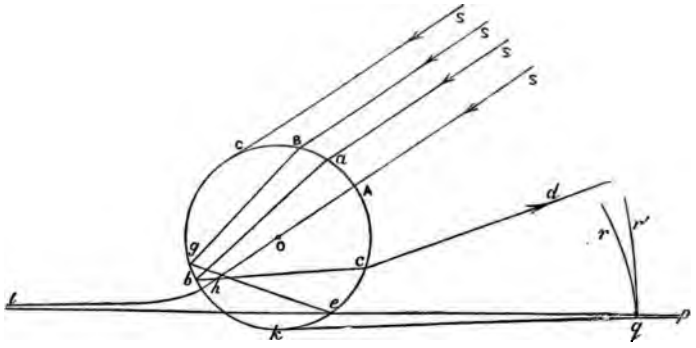
Fig. 77.



in proportion to its focal length, and of spherical figure; but they form a caustic having branches *fa* and *fb*, and the interference near such points as *n* and *p* are seen with an eye-lens E to be brilliant and black rings, the inner ones coloured on their edges, for the same reasons as Newton's rings are seen coloured, and the outer edge of the outer ring shades away to darkness. Sometimes it would be desirable to illuminate the globule *d* by the sun's light coming directly through an aperture in the middle of the mirror A, in which way the author exhibited the experiment at the Meeting of the British Association at Cambridge in 1833.

The rainbows are formed by the interference of rays which have been refracted and reflected within the drops of rain. The

Fig. 78.



primary rainbow, which is the brightest and most frequently seen, is formed by parallel rays coming from each point of the sun's disc, which are refracted on entering the rain-drop, then falling on the further surface are partially reflected, and then meeting the front surface of the drop after emergence from it, come to the eye.

Now the ray SA coming from the sun, which falls perpendicularly on the drop, falls also perpendicularly on the further surface at *h*, and is reflected directly back again in *h*AS. A ray S*a*, which is incident at *a*, will be refracted in *ab*, and the reflected part will pass in *bc*, and be finally emergent in *cd*, which is inclined to AS. As the points of incidence are further from A, we come to a point B, where the ray is refracted in B*g*, then reflected in *ge*, and emergent in *ep*; and *ep* makes a larger angle with AS than any other ray, because beyond B and up to C, where the ray only touches the drop, the rays after refraction, reflexion, and emergence, make smaller angles with AS than *ep* does. From this it is seen that the rays falling on the rain-drop on either side of B, having after emergence all less deviation from the direction AS than *ep* has, there is a double light within the angle formed by AS and *ep*, which will interfere. When we trace the caustic[*], we find that the rays incident between B and C intersect along a branch *kq*, and those which are incident between A and B, if produced backwards, would intersect in a branch *hl*; the line *ep* produced in both directions is the asymptote to these branches, or the line to which they approach without limit but never touch. The luminiferous surface now has the branches *rq* and *qr'*, as formed by the unwrapping of threads from the branches of the caustic, and these are in a state to interfere.

The explanation of the rainbow by Antonius de Dominis, which was adopted by DesCartes, and afterwards completed by Newton[†] when he had discovered the unequal refrangibility of the different colours of the solar spectrum, was as follows:—the whole rays incident between A and C are emergent within the angle between AS and *ep*, but near the direction *ep*, where the angle between AS and the emergent ray has come to a maximum, they are much more condensed together, and afford a much brighter light than in other directions; besides, this brighter light will be more striking from being contrasted with darkness outside the caustic. The separation of the colours in the rainbow was shown by Newton to arise from the different values of the refractive index giving different values for the maximum angle between *ep* and AS.

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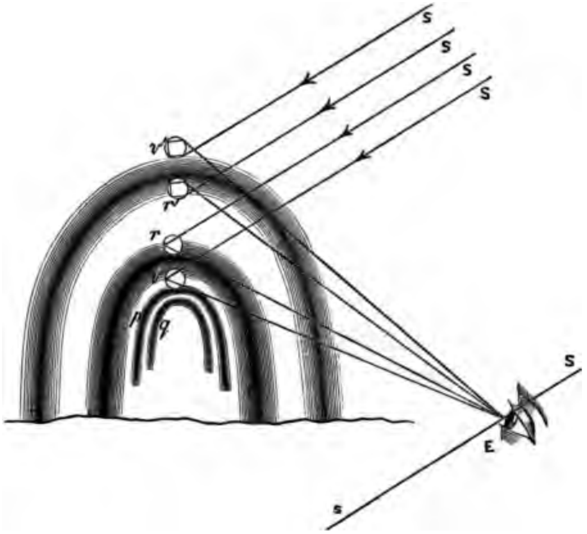
[*] Camb. Phil. Trans. vol. vi. p. 141.

[†] Newton's 'Opticks,' p. 147.

Dr. Young accepted this solution*, but applied in addition the doctrine of interferences to explain the supernumerary rainbows frequently seen within the primary, and sometimes exterior to the secondary rainbow.

If E in figure 79 were the position of the eye, then parallel rays coming from the sun, and falling on the rain-drops to form the primary or inner rainbow, would give the maximum angle of the former figure greater for red than for violet, so that the red would reach the eye from a drop *r* higher than the drop *v*, from which the violet would come to the eye.

Fig. 79.



Now the radius of the rainbow is measured in degrees from the line SE*s* of the shadow of the eye of the observer, and equals the angle between the incident and emergent rays for any particular colour, or it is the angle *r*E*s* for the red of the primary bow, and the angle *v*E*s* for the violet.

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* Phil. Trans. for 1803.

The secondary rainbow, which is seen outside the primary, as in figure 79, and much fainter, is formed by rays which have been twice reflected inside the drop. The red is on the inside, and the violet on the outside, or the angle *r′*E*s* for the red is less than *v′*E*s* for the violet, as in the figure.

Both the bows are symmetrical around the line SE*s* of the shadow of the eye, since the rain-drop, which gives the interference colours, is only required to be at a certain angle with this line; and each drop in the shower furnishes its own rays to the eye, depending on its position.

The drops within the primary furnish each a double light to the eye, which interferes, and often exhibits the supernumerary rainbows *pq* at the vertex of the bows; so also those without the secondary give a double light, which sometimes exhibit supernumerary bows. The space between the bows is dark, but still it furnishes some light to the eye by reflexion at the outer surfaces of the drops. This *externally* reflected light becomes stronger as the obliquity is *greater*, and prevents the tertiary bow, or that formed by three reflexions within the drop, from being generally seen naturally; although that and many higher orders, that is, those which have been formed by light reflected four, five, &c. times within the drop, can be seen artificially, as well as the primary and secondary bows.

Calculating the maximum angle of deviation of *ep* (fig. 78) from AS, with the refractive index $\frac{4}{3}$, it is found to be 42° 2′ if the sun were a point; and since the sun's diameter is 32′, we must add 16′ to the 42° 2′, and have 42° 18′. This was taken to apply to the red by Sir I. Newton, and yet the extreme red light he found extended to only 42° 4′[*]. The accurate measures of Fraunhofer show that the refractive index $\frac{4}{3}$ belongs to the orange light for water, and yet the extreme red was not seen within 14′ of this place[†]. The distance between the primary and secondary bows was measured by Newton to be 8° 30′, but even calculating for orange light, and refractive index $\frac{4}{3}$, the distance should be only 8° 25′; and when we calculate for red light and Fraunhofer's letter B, we find the distance should be only 7° 25′, or the two bows in observation are found 1° 5′ more distant than they ought to be according to theory.

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[*] Newton's 'Opticks,' p. 153.

[†] Phil. Mag. for July 1838, p. 11.

It is clear from these considerations that the old theory of the rainbows was defective, and gave their positions considerably different from the reality.

Mr. Airy, applying the principle* of Huygens, modified by Fresnel, to the interference near a caustic, found the brightest part should be within the caustic, but the brightness should be nearly half the brightest at the caustic, and the light extending outside should gradually shade away to darkness. The natural phenomena clearly did not correspond with this solution; but it received a spurious verification from Professor W. H. Miller†, who made measures of the analogous phenomena seen in a small stream of running water, according to the method of M. Babinet. It appears‡, that, from the refractive index being slightly diminished in such a stream about to break into drops, or from some other cause such as a vibratory form of the stream, the light can be traced considerably outside the place of the caustic as calculated for still water; but when we use a drop of water at rest, the phenomena are in accordance with the natural rainbow, and the undulatory theory, on no view which has been adopted, will solve them.

The iris or artificial rainbow, seen in a drop of water at rest, is an interesting phenomenon, and when a line of light can be used, it is easy to try the experiment.

A tube of glass being drawn out to a fine extremity by the blowpipe, may have a drop of water hanging from its lower end, as at *a* (fig. 80), when it is held vertical, in the following manner:—

The outside of the tapering part near the lower end is to be slightly rubbed with oil, which will prevent the water running up it by capillary attraction; then water being passed into the inside of the tube, at the upper end, some will generally run and drop out, but a portion will remain in the inside from capillary attraction. Let then a small piece of wood, a little less than the inside of the tube, be prepared for a piston, as shown at the upper end of the tube in the figure: this having a little cloth wrapped round it, and being wetted with water, will act as an air-tight piston, and when pushed into the upper end of the tube will cause a drop of water to pass out, and hang from the lower end, as $a$ in the figure.

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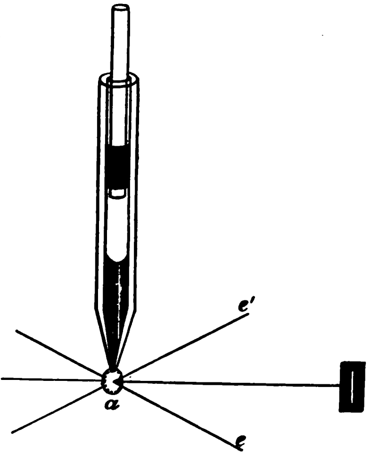
* Camb. Phil. Trans. vol. vi. p. 379.

† Ibid., vol. vii. p. 277.

‡ Phil. Mag. for May 1855.

Fig. 80.



In such a drop the iris is seen very beautifully, when the sun's light reflected through a narrow aperture to form a line of light, as in the figure, falls upon the drop at the distance of a few feet. When the eye is placed near the drop the primary iris will be seen; when the rays entering the eye, as $ae$, make an angle of about 42° with the ray that falls perpendicularly upon the drop: there will evidently be an iris seen similarly on the other side of the perpendicular ray, as in the direction $ae'$. Now if we can measure the angle $eae'$, we have only to take the half of it for the augle of $ae$ or $ae'$ from the perpendicular ray; and this is, in the natural rainbow, the radius of the primary bow. In the experiments, the extreme red could be traced only to about 42° 23′, at which distance darkness occurred; and yet for the red of Fraunhofer's letter B, the asymptote of the caustic is at 42° 22′.

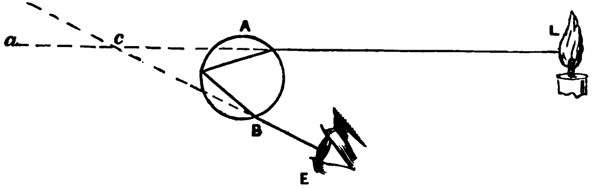
The angle $eae'$ may be measured very simply by setting up two needles in an arc drawn, with its center below $a$, on a table, in the directions continued beyond the drop in which the rays enter the eye, and then measuring the angle, which equals $eae'$, between them. The means used by Professor Miller with the stream of water, and by the author with the stream and drop, to measure the angle $eae'$, was to have a well-divided brass circle (a protractor) placed horizontally on a table, with its center under the stream or drop $a$; and the observations of the rays $ae$, $ae'$ were made with a small simple telescope supported on the moveable arm of the circle. This telescope, with single object and eye-glasses, does not need to be thicker than an ordinary drawing pencil, and four or five inches in length; and it may magnify distant objects from three to ten times, according to the measures required to be taken. If the extreme angles of the different colours are only required, then a magnifying power of three times is sufficient; but if accuracy in measuring the *successive* distances of the interference maxima of brightness is required, a higher magnifying power will be necessary. The telescope must be adjusted to show *distant* objects distinctly, and must have cross hairs put in the common focus of its object and eye-glasses, which being seen together with the interference phenomena, enable us to bring them to the same point of the field of view in taking the measures.

On account of the mixture of colours the interference arcs are not numerous when seen in ordinary sunlight; but when we place a piece of red glass before the eye, the number of alternations of bright and dark arcs visible, is very great; in one experiment the author counted upwards of forty bright arcs with intervening black ones.

If a small cylinder of glass be ground and polished, the interference near the caustic may be seen with light direct from the sun, when there have been many internal reflexions. Some of the cases may be seen by the light of a candle, and with cylinders prepared by melting a piece of glass in the fire, or with a blowpipe, and drawing it out into a small rod of the thickness of a thick pin, whilst soft.

The small cylinder must be held near the eye, and a little oblique, so that the light reflected at the outside may not obscure the interference iris.

Fig. 81.



With the cylinder of glass AB in figure 81, taking the refractive index $\frac{3}{2}$, we find the caustic, or rather its asymptote, for the primary iris, would make, with the direction of the incident light L*ca*, the angle I*ca*, which equals L*c*E, equal to 22° 54′; the red having the greater, and the violet the less angle.

The asymptote of the caustic for the secondary iris makes, as seen by the eye, the angle 86° 50′ with the direction *ca*; the violet light entering the eye now making a greater angle with *ca* than the red light. These are easily seen by candle-light.

The asymptote of the caustic for the tertiary iris makes the angle 9° 6′ with the direction AL, the violet making the larger angle. As we have now to look nearly towards the light L, the light reflected at the surface of the cylinder prevents the iris being readily seen; with sunlight and care it may be however seen very brilliant.

The asymptote of the caustic for the fourth iris, or when there have been four internal reflexions, makes the angle 71° 4′ with *ca*, the violet making the less angle. It is much easier to find than the last.

The asymptote of the caustic for the fifth iris makes the angle 27° 24′ with *ca*, the violet making the larger angle. It is a faint iris a little outside the primary one.

The asymptote of the caustic for the sixth iris makes the angle 54° 40′ with the direction AL, the violet making the less angle. It is not so easy to find as the last.

The asymptote of the caustic for the seventh iris makes the angle 43° 0′ with AL, the violet making the larger angle. It is difficult to find.

The asymptote of the caustic for the eighth iris makes the angle 39° 52′ with the direction of *ca*, the violet making the less angle. It is easier to find than the two last.

The asymptote of the caustic for the ninth iris makes the angle 57° 26′ with *ca*, the violet making the larger angle.

The asymptote of the caustic for the tenth iris makes the angle 25° 50′ with AL, the violet making the smaller angle.

We must remember that in all these cases we shall have darkness at the calculated place of the caustic, and the bright interference will be near it, but towards the place of the caustic for the more refrangible rays.

## ON THE INTERFERENCE OF POLARIZED LIGHT.

The discovery of the interference of polarized light was made by M. Arago*. Dr. Young had recognized the circumstance, that when light had traversed a plate of a double refracting crystal, as for instance a natural plate of mica or selenite, one of the rays was retarded behind the other, and yet no interference was exhibited in ordinary light. When M. Arago placed such plates in polarized light, and examined the light transmitted by them with an analyzing apparatus, the interference became visible, and was exceedingly beautiful and interesting.

The reasons for the interference being visible only in these circumstances were discovered† by MM. Arago and Fresnel (see the discussion of fig. 57), who found that light polarized in one plane did not interfere to produce changes of brightness, with light polarized in the plane at right angles to it. The following is the enunciation of the laws by M. Arago‡:—1. "Two pencils converted from natural light into light polarised in the same direction, retain, after this modification, the property of interfering with each other. 2. Two pencils, which are made to pass directly from the state of natural light to that of light polarised in two perpendicular directions, are no longer capable of interference, either while they remain in this state, or after they have been restored to a similar polarisation. 3. Two pencils polarised in contrary directions, do not interfere, whatever may have been the modifications that they have undergone before they arrive at this state from that of natural light; but when restored to a similar state of polarisation, they become capable of interfering, provided that in their passage from the natural state to that of polarised light THE FIRST planes of polarisation of the two pencils were parallel."

The latter part of this third law shows the arrangement of the apparatus to be employed in every case, in order to witness the interference of light which has traversed small double refracting crystals as seen in the microscope, or double refracting plates of mica, selenite, quartz, &c. That is, *the light must be polarized before traversing the double refracting plate or crystal, and must be analyzed after emergence from it.*

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* Mémoires de l'Institut for 1811.

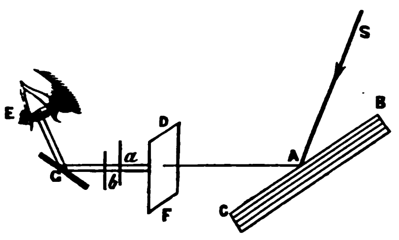
† Annales de Chimie et de Physique for 1819, tome x. p. 304.

‡ Article 'Polarisation,' addendum to vol. vi. Supplement to the 'Encyclopædia Britannica,' by M. Arago.

The retardation depending upon the difference of the velocities with which the two rays traverse the plate or crystal, and on the thickness so traversed, it is clear the interference depends on these also. Now the difference of the velocities near the optic axes of crystals changes quickly with the change of inclination of the rays to the optic axes; therefore, to see the whole phenomena, we require to bring the crystallized plate very near the eye, in order to receive rays at various inclinations, and for which the tourmaline has great advantage as an analyzer. In other cases, the retardation, as produced by the thickness of the plate, being most important, the effects are seen at any and various distances from the eye, and then Nicol's rhomb, being free from colour, would be much preferred as an analyzer. Both cases may be well seen, however, by an analyzer consisting of a small piece of common glass placed *near* the eye at the polarizing angle.

Let BAC be a pile of several plates of glass set in a convenient frame; DF a thin plate of mica, selenite, or other double refracting crystal; G a small piece of glass blackened at the back by a coating of black sealing-wax. Then the polarizing pile of plates BAC, and the analyzer G being set at the polarizing angle, an incident beam of light, of which SA is one of the rays, will be polarized after reflexion by the pile CB, and on transmission by the double refracting plate DF, each ray will be generally separated into two, which will pass through it with different velocities, and after emergence one will be retarded behind the other, as at *a*, *b*, and after being analyzed by the plate G, the light entering the eye at E will exhibit the interference. The interference in such an experiment is generally seen as a splendidly coloured light,

Fig. 82.



which is the more astonishing and pleasing as being produced by colourless substances. To those ignorant of optical phenomena the results are especially surprizing. The colour arises in this manner:—certain coloured rays having such retardation as to destroy each other, and other coloured rays such as to strengthen each other's effect, the latter shine out brilliantly, whilst the former produce darkness, intermediate rays producing intermediate effects, and a coloured beam hence arises from an original white one.

The plate DF remaining fixed, the colours change by turning the analyzer G round the direction AG; and they become complementary every 90° of the rotation, that is, the two tints exhibited at angles 90° distance will, if taken together, produce white light.

It is for this reason that the light which has traversed the plate DF does not show the interference until analyzed, since ordinary light is equivalent to two equal beams polarized in planes at right angles to each other. With mica, selenite, and biaxal crystals generally, the colours change also by turning the plate DF round the line AG.

Selenite not only cleaves easily with a penknife to various thicknesses, but can be scraped into wedges with a knife, and have letters and various devices cut or engraved upon it, and then have the polish sufficiently restored by rubbing with a soft cloth wetted with water: the plate can then be cemented with Canada balsam between two pieces of window-glass, and conveniently preserved.

Selenite wedges, with their edges made as fine as possible, and being half an inch broad, their backs not thicker than thick paper, prepared in this manner, show the effect of the different thickness in different parts upon the interference in a very satisfactory manner; a series of coloured bars parallel to the edge of the wedge being exhibited, and the colours recurring as the retardations increase by $\lambda$, $2\lambda$, $3\lambda$, &c., as in Newton's rings. When two such wedges are crossed at right angles, the bars become diagonal where they cross each other, and form interesting effects as the analyzer is turned round.

Nearly every tint of colour may be obtained in the films split thin with a penknife, from a crystal of selenite. Selenite designs, which show beautiful figures of butterflies, flowers, &c. in the polarizing apparatus, are made by choosing films of selenite of the requisite thickness, cutting them into the shapes required, and cementing them between plates of glass with Canada balsam in the proper positions. These selenite designs, to the naked eye appearing like pieces of glass with scratches upon them, become beautiful designs magnificently coloured when placed between the polarizing and analyzing plates.

Pieces of *unannealed* glass are sometimes prepared of various shapes in the flint-glass houses, which, when placed at DF, exhibit very beautiful coloured curves and spaces. When the pieces of glass are of regular forms, the interference colours are of symmetrical forms also. A piece of a cylindrical rod of unannealed glass, with the ends cut perpendicular to the length, ground and polished, shows a series of coloured rings round the axis, with a black cross through the center, when the plane of analyzation is perpendicular to the plane of the original polarization, and a bright cross when those planes are parallel; these are like the rings and crosses of uniaxal crystals, as described further on. The law of the retardation, as given by Brewster*, is, however, different in these cases from that for the crystals.

Analogous phenomena are seen in many other circumstances, such as gelatinous bodies (like the eyes of fishes) which have dried unequally; when transparent bodies are subject to pressure or flexure; when those crystalline bodies which generally have no double refraction, have crystallized irregularly; when glass and crystals are subject to unequal temporary heating or chilling; and when glass is under the action of powerful electro-magnets. In these cases the particles of the bodies are in states of restraint, which give rise to small degrees of double refraction.

Physical optics here give a proof of what would be difficult to show otherwise; namely, that in a mass of matter the particles have a dependence on each other, which propagates through the mass a disturbance arising from one which is applied to only particular parts. This is well seen by taking two equal portions of the same cylindrical rod of glass, ground and polished at their ends; and after comparing the rings they exhibit in the polariscope to see that they are the same, then rubbing away on a rough stone a portion of the side of one of them, it will be seen that the interference rings throughout the whole mass have become changed, and consequently the removal of a part of the body has affected the particles through the remaining mass.

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* Phil. Trans. 1816; Phil. Trans. Ed. 1818; 'Optics,' edition of 1853, p. 324.

An interesting experiment on these phenomena may be tried with very simple means, and in a very short time. Pieces of window-glass being prepared for the polarizer and analyzer, as in fig. 82, take a *thick* piece of crown, plate, or flint glass, with polished parallel faces, heat it to redness in the fire, and then chill its edges by placing them on a piece of cold metal. On examining it in the polarized light when cool, it will generally be found to exhibit interesting coloured curves and spaces, from the slight double refraction produced by the unequal cooling of the different parts.

This experiment shows the importance of the proper annealing of articles made of glass, which, as is well known, are more liable to break when the annealing is imperfect, from the state of unequal restraint in which the particles have been left.

The irregular and macled portions of crystals sometimes exhibit very beautiful phenomena when examined in this polarizing apparatus. Macled amethyst*, and crystals of sulphate of potash, are amongst these.

In many of the above substances the double refractive energy was so small, that considerable thickness might be employed without the retardation of one ray behind the other being too great to render the interference bands visible. In crystals of strong double refractive power it is only near the optic axes that the retardation is small enough to render the interference visible in the ordinary polariscope for plates of *moderate* thickness. The double refraction being symmetrical with regard to the optic axes, the interference is shown in rings and other curves, which have forms symmetrical to them also, and afford very splendid appearances. Though these may be well seen with such an analyzer as in figure 82, yet as the tourmaline has a great advantage, we will now suppose it to be the analyzer.

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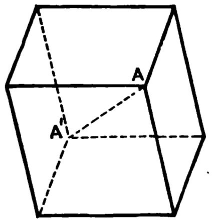
* Brewster's 'Optics,' p. 291, edition of 1853.

Referring to the chapter on double refraction, the rhomb of calc-spar, as in the figure, having equal edges, the line AA′ joining the obtuse summits is the optic axis of the rhomb; but all lines parallel to it in the crystal are the optic axes of their respective parts. Now a plane perpendicular to AA′ will be perpendicular to such a system of parallel lines. If a plate of $\frac{1}{10}$th to $\frac{1}{20}$th of an inch thick, with its two parallel faces *perpendicular to AA′*, be formed of a piece of calc-spar by grinding off the summits at A and A′, and then repolishing the faces with putty powder, fine red oxide of iron, or jeweller's rouge and water, upon a surface of pitch mixed with a little ordinary wheat flour, we have it similar to the figure DF (fig. 83).



Let BAC be the polarizing plates of glass, DF the plate of crystal, G the analyzing tourmaline, E the place of the eye. Then DF, G and E being near together, and also near the polarizing plates, the eye will receive rays which have passed through DF at very different inclinations, and the systems of rings and brushes will be seen in great perfection. Other methods may be used with advantage, and the inclination of the rays increased by employing lenses for that purpose, but the above is a simple and convenient method. For the support and mounting of the plate of crystal DF and the tourmaline G, a ring of wood, AB (fig. 84), about 1 inch in diameter and ¾ths of an inch broad, with a disc DC fitting so as to turn round in it, may be used. The ring AB shows the crystal cemented to the end of a piece of

Fig. 83.

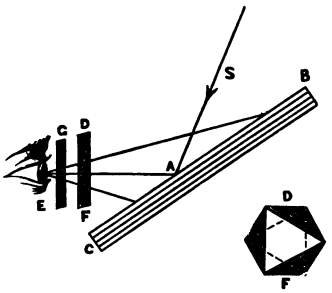
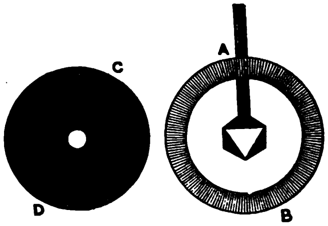


Fig. 84.

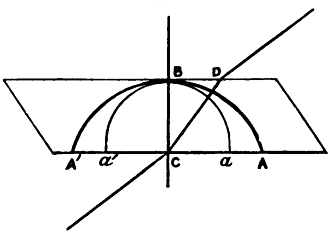


wood passing through a hole in the ring, and fixed with wedges in the proper position. The disc CD shows the aperture in its center where the tourmaline plate is cemented. The same mounting is convenient for the support of all plates requiring to be brought near the eye.

Now in the chapter on double refraction, it was shown that in a uniaxal crystal, the ordinary and extraordinary rays travel along the optic axis with the same velocity, and have therefore no retardation the one behind the other, but those which are inclined to it travel with different velocities, represented within the crystal by the radii of a sphere and a spheroid.

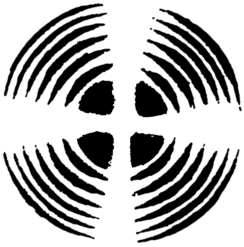
Suppose the figure 85 to represent a plate of calc-spar cut perpendicularly to the optic axis BC. If C were a luminous point on the lower surface, two corresponding luminiferous surfaces would expand in the forms of a sphere and a spheroid, of which, on arriving at B, the sections would be a circle, as $aBa'$ for the ordinary, and an ellipse $ABA'$ for the extraordinary light. Now the two rays would have no retardation along BC, but in any other direction, as CD, the ordinary ray would be retarded behind the extraordinary one. It is shown that near the optic axis the retardation varies as BD squared, nearly, and as will be found by referring to the discussion of figure 69; this is similar to what occurs in Newton's rings, and like them, the interference rings formed round BC are narrower as they are further from the center, and coloured in a similar manner to what they are. It has been supposed that C was a luminous point, but if two rays were refracted along DC, from rays incident at D or C, the same retardation would arise.

Fig. 85.



There is one respect in which the analogy with Newton's rings does not exist, and which arises from the laws of polarization. First, let the planes of polarization and analyzation coincide with the plane of incidence, and be taken for the plane of the paper in figure 83; then the rays which pass through the plate DF in this plane will furnish ordinary refracted rays only, and there will be no interference, but after analyzation a bright bar of light; again, perpendicular to the plane of incidence, the rays passing through the plate DF will go to the extraordinary rays entirely, and there will be another bright bar perpendicular to the former. We have thus a bright cross with segments of a series of coloured rings, commencing from a bright center, as in figure 86 *a*. Secondly, let the planes of analyzation and polarization be at right angles to each other. Then in the plane of incidence the light undergoes, as before, ordinary refraction only on traversing the plate GF, and on analyzation in the plane at *right angles* produces a dark bar. Also, in the plane at right angles to the plane of incidence there is only the extraordinary ray with no interference, and on analyzation it produces another dark bar; so that the rings commence from a black center, and have a black cross passing through them, as in fig. 86 *b*.

Fig. 86 *a*.



When the planes of polarization and analyzation are neither parallel nor perpendicular, there is an eight-rayed neutral tint star, with the segments of rings commencing from bright and dark centers in the alternate sectors.

Fig. 86 *b*.

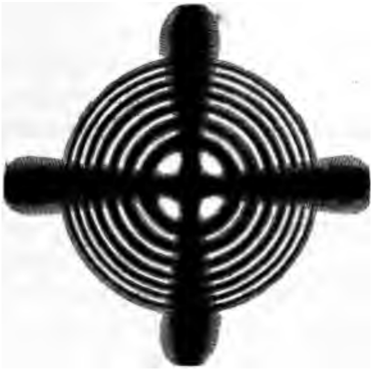
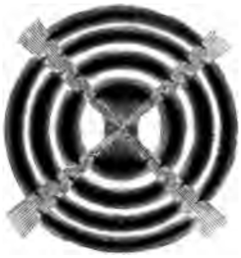


Fig. 87.

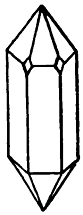


The above are the phenomena presented by uniaxal crystals generally, such as plates of ice as they are taken from the surface of water, uniaxal mica, &c.

When the light is either circularly polarized before passing through the plate DF, or circularly analyzed after traversing it, there is seen a neutral tint cross in all relative positions of the polarizer and analyzer; the bright segments of rings in one quadrant correspond in radii to the dark ones of the adjoining segment, as represented in figure 87.

When the light, before entering the uniaxal plate, is circularly polarized, and when emergent from it is circularly analyzed, the crosses disappear, and the rings are seen complete.

Fig. 88.



Quartz crystal, often found, as in figure 88, a six-sided prism with pyramidal terminations, though ranked with uniaxal crystals, has peculiar double refraction. The crosses, dark or bright, are not distinctly shown near the center, and the central space of the rings is coloured with tints depending on the thickness of the plate, and the angle between the planes of polarization and analyzation.

The varying tints along the axis show that the two rays travel along the optic axis of the crystal, which is the axis of the six-sided prism in the figure, with different velocities. With a piece of crystal one to two inches long, and a minute hole in tinfoil on the first surface, the two rays can be examined with a magnifying eye-lens attached to the analyzer as they approach the optic axis; and it will be found from the analyzation that they cease to be plane polarized, as they do not disappear at any position, when rotation is given to the analyzer; and this becomes more evident as the rays approach more nearly to the optic axis.

When thin plates were used, M. Biot* discovered what appeared to be a rotation of the plane of polarization of the beam of light produced by its traversing the plate cut perpendicularly to the axis, and which he has denominated rotatory polarization.

When a number of plates of equal thickness have been obtained, say $\frac{1}{25}$th of an inch thick, by placing them at DF (fig. 83), first one, then two together, then three together, &c., it is said we find a rotation of the plane of polarization through an angle proportional to the thickness of the quartz plate which the light has traversed, but different for the different colours of the spectrum. Before any plate is interposed, let the planes of analyzation and polarization be at right angles, and the field of view will then be dark; let now one of the plates be interposed, and the field will be no longer dark, but it will be rendered dark again in homogeneous light, by turning the analyzer through a certain angle. Place a piece of red glass before the eye, and the field is rendered dark by turning the analyzer through about 20°. Place a piece of green glass before the eye, and it is rendered dark again by turning the analyzer through about 28°. With a piece of blue glass, it must be turned about 33° to render the field dark again. If two of the quartz plates be interposed together, the analyzer must be turned through the double of the above angles to reproduce the dark field; and if three be interposed, it must be turned through three times these angles, and so onwards for any number of plates, or for a single plate of their united thicknesses.

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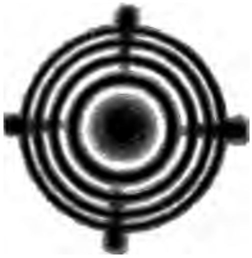
* Annales de Chimie et de Physique for 1818, tome ix. p. 372.

It is supposed in the theory of rotatory polarization, that when the field of view is dark, the light is polarized in a plane at right angles to the plane of analyzation; when, however, we take into consideration the laws of interference, we know that a dark field may be the result of interference where the rays have a retardation, one behind the other, arising from their having traversed the quartz plate with different velocities. M. Fresnel showed that the above phenomena were explicable on the supposition that the two rays passing along the axis of quartz are circularly polarized, one right-handed, the other left-handed (see fig. 39); and that they traverse the axis of the crystal with different velocities. Mr. Airy* extended this theory by considering the light passing in any direction through a crystal of quartz as elliptically polarized, becoming plane polarized perpendicular to the axis, and circularly polarized along it.

Fig. 89.



The figure 89 was drawn from a piece of crystal placed in the polariscope, of such thickness that in homogeneous red light the center was dark when the planes of polarization and analyzation were at right angles to each other. The black cross became visible, but only faint at the second ring. On turning the analyzer round one way, whilst the polarizer was stationary, the central dark space and the rings around it increased in magnitude until a bright space began to appear in its center, and the rotation being continued, this increased until it arrived at its brightest, and then a darker space appeared in its center, which increased in diameter, and its middle part became darker until a black center was formed as at first, when the planes of analyzation and polarization were again at right angles; and so onwards through the same changes as before. If the analyzer were turned the other way round, the central spot and rings diminished in size, and followed analogous but reversed changes to the former ones.

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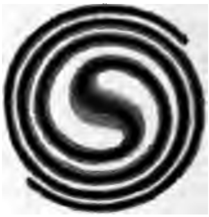
* Camb. Phil. Trans. for 1831, vol. iv. p. 81.

The formation of the black cross within a small distance from the axis, as in fig. 89, shows that the deviation from ordinary uniaxal crystals becomes only very evident within that distance. By means of an instrument called a *compensator*, M. Jamin* has measured the degree of ellipticity of the rays at different angles from the axis, and confirmed approximately Mr. Airy's theory, that the two rays must be considered as generally elliptically polarized. Mr. Airy has given his solution of the general interference phenomena in the Cambridge Phil. Trans. vol. iv. on this theory. He found that if the light were either circularly polarized before entering the quartz plate, or were circularly analyzed after emerging from it, the interference curves would become spirals. The figure 90 was drawn from the piece of crystal above mentioned, when the curves appeared the most symmetrical in red light.

Fig. 90.



The brilliant colours exhibited by quartz may be very well studied with plates $\frac{1}{8}$th to $\frac{1}{10}$th of an inch thick; but to see the spirals well, a piece $\frac{3}{8}$ths of an inch thick is better. A piece of a fine crystal of $1\frac{1}{8}$th of an inch thick, possessed by the author, shows only pale pink and green rings, but it shows the black cross of uniaxal crystals, commencing at the second ring, much better than the thinner pieces.

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* Annales de Chimie et de Physique for 1850, tome xxx. p. 55.

Thin plates of quartz may be obtained from the workers in Brazil pebbles (which are quartz) for spectacle glasses, by getting them to cut the crystals which are too small for such glasses perpendicular to the axis of the crystal. A quartz crystal accidentally met with may be soon prepared for experiment as follows:—Grind off the summits of the crystal, and bring the surfaces to be as smooth as possible, and then they are polished quickly by rubbing them with water on a piece of the whetstone called Water-of-Ayr stone.

Quartz crystals are found in two varieties, called right-handed and left-handed crystals; in the first kind the apparent rotation of the plane of polarization takes place to the right hand, and in the latter to the left hand. These two varieties show the spirals of fig. 90, turning in opposite directions when *similarly* treated.

Sir John Herschel discovered* that the particular variety to which a crystal belongs is shown by the way the small facets, frequently met with, as at the junction of the upper pyramid and prism in fig. 88, are inclined.

These varieties are explained on the theory of M. Fresnel by the right-handed circularly polarized light traversing the axes of some crystals quicker than the left-handed, and in others the reverse.

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There are many liquids which have properties similar to those of quartz near the axis, such as essential oils, and solutions, as those of cane and grape sugar, of tartaric acid, of dextrine (British gum—prepared by baking starch, or treating it with sulphuric acid), which has received this name from its giving apparent rotation of the plane of polarization to the right hand, and to a large amount; besides many other solutions and many vegetable juices.

The observations with these liquids may be well made in the way above described for plates of quartz with homogeneous red light, and a divided circle to measure the rotation of the analyzer, the liquid being contained in a tube with plates of glass closing the ends, like B (fig. 91).

The laws are the same as for quartz, but with the amount of rotation† varying for the different liquids.

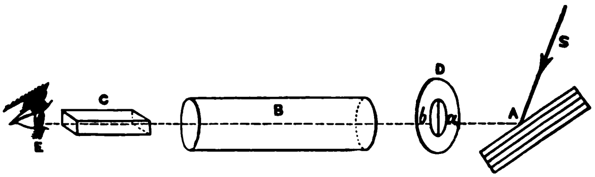
* 'Treatise on Light,' art. 1042.

† See M. Biot's paper, Annales de Chimie et de Physique, 3rd series, tome x. p. 20; also the same work for 1850, tome xxix. p. 215.

In solutions, such as those of sugar, the amount of apparent rotation depending on the space of the solution traversed by the light, and on the strength of it; it has been proposed to ascertain the value of syrups, and other liquids by this property.

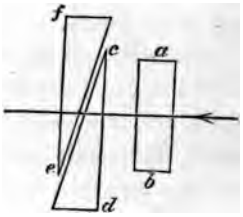
M. Soleil, the celebrated instrument maker of Paris, has adopted the following method, as capable of furnishing the value of these solutions to increased accuracy. Let A represent the polarizer, D a disc, having in its center an opening, in which is placed a circular plate of quartz, of which one half as *a* is right-handed, and the other as *b* left-handed; B the tube, with glass plates at the ends, containing the syrup or solution; C an analyzer, such as a double image rhomb, or Nicol's rhomb. Now before the tube B is interposed, the analyzer may be turned round until the *two parts* of the quartz plate in D show each the same rich purple tint (or *couleur sensible*); and then when the tube B is interposed, the rotation to be given to the analyzer to reproduce this tint in both parts can be found with considerable accuracy.

Fig. 91.



Another method is, by means of the refined and important instrument, the compensator of M. Babinet, of which the principle is as follows. Let *ab* be a plate of one of the varieties of quartz in fig. 91 *a*, cut perpendicular to the axis of the crystals *cd* and *ef*, two wedges cut in like manner from a crystal of the other variety. The two wedges, on being moved in opposite directions, furnish a plate of variable thickness, which can be brought to compensate the effect of the plate *ab*. That is, in one of these plates the retardation of one of the circularly polarized rays is as much as its acceleration in the other, and the combination acts as if it

Fig. 91 *a*.



were only a piece of well-annealed glass, producing no change in a polarized beam passing through it, as ascertained by placing it between A and C (fig. 91), when B and D are removed. Then the compensator in its mounting, with rack-work and divided scales, being placed near C, when the tube B with its contained solution is interposed also, it will be found that the compensation no longer exists, but it may be restored by giving a fresh position to the wedges *cd* and *ef*. The change in the positions of the wedges determines the effect produced by the solution in B, and hence determines its value.

The principle of the compensator is one of great value in other arrangements, and has furnished, in the hands of M. Jamin, very important results.

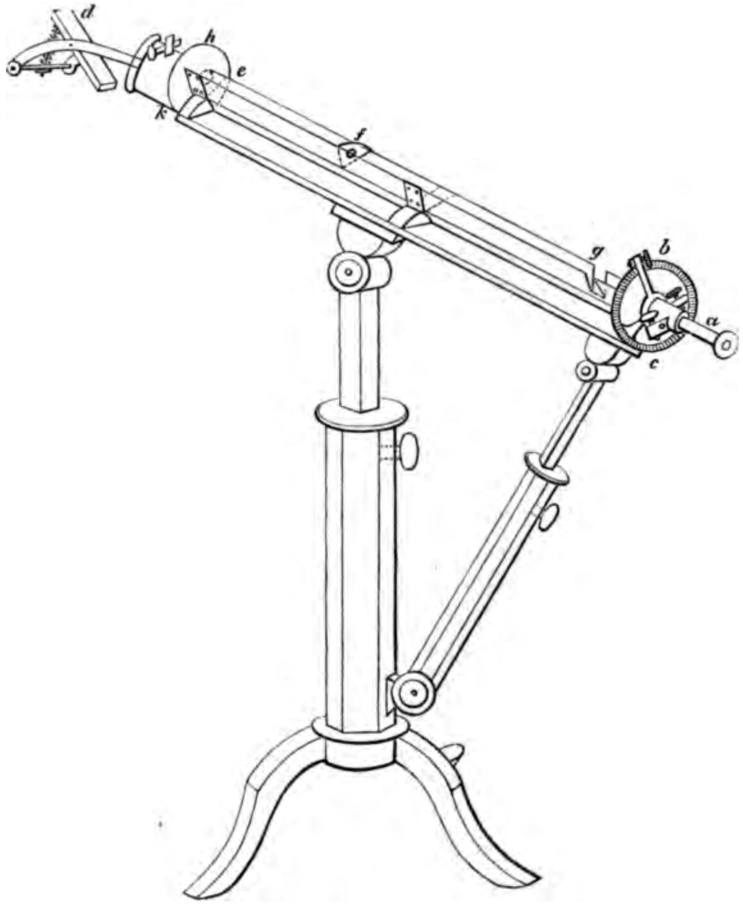
The large polariscope of M. Duboscq Soleil is constructed with an especial view to these and other important experiments. The figure 91 *b* of this instrument is drawn from one belonging to the author, a valuable present from an esteemed scientific friend. At *a* is a small opera-glass, which being adjusted to show distinctly an aperture in the circular plate *hk*, is of great advantage in most experiments; it screws to the tube carrying the analyzer, a double image rhomb. This rhomb can be moved round, and clamped in any position within a tube, connected with the arm of the vernier, and turning round in a circular aperture in the center of the divided circle *bc*. This can also be clamped to the circle in any position.

The polarizer is either a plate of glass as at *d*, or a double image rhomb, one of whose images, on account of the length from *h* to *b*, falls out of the way. The polarizer is capable of rotation, and clamps in any required position.

The light of the polarizer is thrown through any required aperture adapted to the circular disc *hk*, which has a circular hole in its middle; as for instance the disc D (fig. 91), a narrow slit to make a line of polarized light, as in fig. 96, or any other required form of aperture.

The objects to be examined are placed somewhere in the angular trough *efg*, between two plates of metal. At *f* is shown a moveable metal screen, with a circular hole in its middle, to be clamped anywhere to the trough; this may be used to support objects to be examined, or films of mica to produce retardations between two rays polarized at right angles, or otherwise to act as a simple perforated screen.

Fig. 91 *b*.



At *g* parts of the sides of the trough are cut away to admit the mounting of the compensator.

The uses of the other parts which are drawn will be seen at once, and the various tube apparatus for the experiments with liquids, and these also at different temperatures; as well as the changes in order to try the experiment (fig. 96); the mounting of the compensator, and many other experiments, it is unnecessary to draw.

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The interference phenomena, exhibited when plates of biaxal crystals are placed at DF (fig. 83), are very various and beautiful. When the axes are much inclined, we can see only the rings, and the single brush of one axis at a time; but when they are not much inclined to each other, we can see the lemniscate curves, ovals and brushes for both axes together.

Thin plates of arragonite, say $\frac{1}{10}$th of an inch thick, cut perpendicular to the line bisecting the optic axes (see fig. 20), show the phenomena round both axes well, but not better than can be obtained easily with similar pieces of common saltpetre. The prisms of nitre on being cut across will generally be found irregularly crystallized in their interior; but by searching, especially amongst the rough saltpetre, pieces will be found which are transparent, of regular crystallization, and of sufficient size for the purpose when brought close to the eye. A plate of this being cut perpendicular to the axis of the crystal, and the faces made as smooth as possible by scraping with a sharp knife, a sufficient polish can be obtained by rubbing with a soft wet cloth. This plate being cemented between two bits of thin window glass with Canada balsam, may be conveniently mounted in the ring of wood (fig. 84), like the calc-spar plate in that figure.

The law of the retardation of one luminiferous surface behind the other, on which the interference depends, was discovered by M. Biot from analogy with the known law for uniaxal crystals. In these latter it was shown that the retardation is proportional to the distance BD squared, of the ray CD (fig. 85), from the optic axis nearly; in biaxal crystals M. Biot's rule is, that the retardation is proportional to the product of the distances $a'p$ and $a''p$ in fig. 41 from the two optic axes. When the two optic axes are close together, and the crystal is nearly uniaxal, the rule becomes nearly that for uniaxal crystals as it ought to do.

From this rule it arises that the interference curves and brushes, when the plane of the optic axes coincides with either of the planes of polarization or analyzation, and they are at right angles to each other, are like figure 92.

The appearances change as the plane of the optic axes is inclined to the planes of analyzation and polarization. When these latter are at right angles as before, but the plane of the optic axes is inclined 45° to each of them, the appearance is like figure 93, with the hyperbolic brushes through the axes.

Fig. 92.

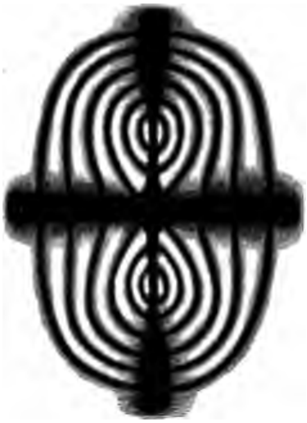
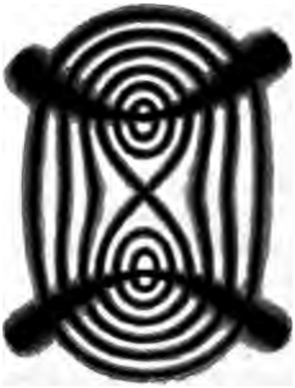


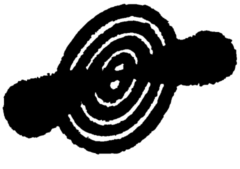
Fig. 93.



When the planes of analyzation and polarization are parallel, there are bright brushes in place of the dark ones in figures 92 and 93 respectively, with dark curves for bright ones, and bright ones for dark ones respectively.

When the optic axes are very much inclined to each other, which is the case in the greater number of crystals, and we can see only the rings around one axis at the same time, we know from two circumstances that the crystal is biaxal, and not uniaxal; first, because there is only a single hyperbolic brush in place of the cross of uniaxal crystals, and secondly, from the law of the retardations the rings are nearly at equal distances, in place of becoming rapidly narrower, as in uniaxal crystals.

Fig. 94.



With a plate of such a crystal, we have the oval rings and brush as in figure 94, when the plane of the optic axes is inclined to the planes of polarization and analyzation, and they are set at right angles to each other.

When the planes of analyzation and polarization are neither parallel nor perpendicular to each other, there are two sets of neutral tint hyperbolic brushes, of which the asymptotes are parallel and perpendicular to the planes of analyzation and polarization respectively.

When the light is *circularly* analyzed or polarized, we have neutral tint hyperbolic brushes, and the dark curves on one side of them correspond to the bright ones on the opposite side analogous to the uniaxal crystals.

When the light is both circularly polarized, and circularly analyzed, the brushes disappear, and the interference curves are seen continuous.

In biaxal crystals generally the angle between the optic axes is different for the different colours of the spectrum, and hence the colours are separated on this account, which produces beautiful shading of the central rings. The angles between the axes have been found to undergo singular changes when heat has been applied to the crystals.

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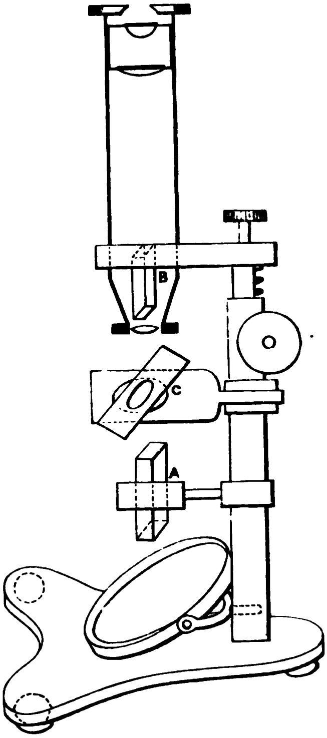
The polarizing microscope applied to minute double refracting crystals, and other bodies, requires similar arrangements to those we have been considering; that is, the light must be polarized *before* passing through the microscopic double refracting crystals, and other bodies, and analyzed *after*. As low magnifying power is only required, generally, the object-glass of the microscope need not be achromatic, although the boundaries of the minute crystals are better shown when it is so. A common pocket microscope will show most of the objects very well.

Any methods of polarization and analyzation may be applied, but the best method is to polarize the light by a Nicol's rhomb, as at A in figure 95, immediately below the microscopic crystals, &c. at C, on a plate of glass laid upon the stage of the microscope; and to analyze by another Nicol's rhomb placed immediately above the object lens, at B, where it can be supported by pieces of cork within the tube. Either A or B should be capable of rotation, so as to allow a change of the angle between the planes of polarization and analyzation.

Fig. 95.



Solutions of the following, allowed to crystallize upon a plate of glass, as at C, form beautiful objects;—salicine, nitre, carbonate of soda, sugar, chlorate of potash, Epsom salts, borax, oxalate of ammonia, boracic acid.

There are many other objects which are best studied in the polarizing microscope; such as the starch globules of potatoes, thin laminæ of agates, many vegetable and animal structures.

With some of the above objects the effects are much improved by placing a thin plate of selenite immediately under the object.

The microscope employed as above furnishes some of the most splendid appearances which can be witnessed.

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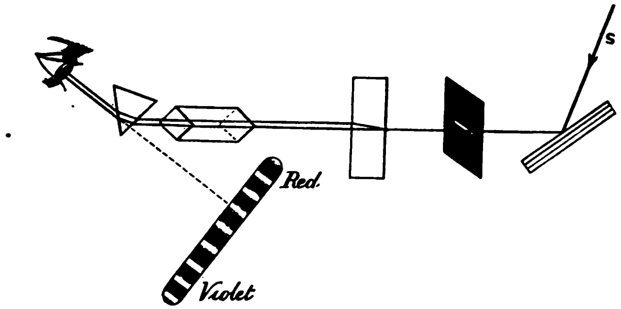
## ON INTERFERENCE WITH LARGE RETARDATION.

In the double refracting plates which have been considered, the thickness was such that the retardation was not a great many multiples of the interval λ, for when the thickness was more considerable, the colours became so mixed that only faint alternations of colour were seen, and when greater still the effects of interference were imperceptible. By viewing many such cases through a prism, according to the method of MM. Fizeau and

Foucault, the interference will be seen in the proper circumstances.

In polarized light, if a *thick* slice of a crystal, such as selenite or quartz, be placed in the ordinary way between the polarizing and analyzing plates, it will appear to have only depolarized the incident light; but if the originally polarized light be restricted to a narrow line, as in figure 96, then on examining the analyzed light through a prism, the visual spectrum will appear as in the figure, made up of bright and dark bars, which are more numerous as the thickness of the crystalline plate is greater.

Fig. 96.



If the analyzation is made with a double image rhomb, the two prismatic spectra are seen at the same time, and it is easily seen that the tints, which are in a state of bright interference in one, are in a state of dark interference in the other. On a rotation being given to the plane of polarization, the bars will be found to ascend or descend in the spectra according to the direction of the rotation.

# CHAPTER IV.

## ON PHOSPHORESCENCE AND PHOTOMETRY.

The property of phosphorescence, which we here consider, must be distinguished from combustion, incandescence, the luminosity of insects, &c., by its being derived from the exposure of the phosphorescent body to light only. The existence of this property is shown by light being dispersed around the body, either whilst under illumination, or for some time after the body has been removed into the dark.

Sir Isaac Newton mentions* the singular appearance of a tincture of lignum nephriticum, and some sorts of glass, which in daylight reflect some colours, and transmit others. Bologna phosphorus, Canton's phosphorus†, and some diamonds, retain their phosphorescence for a considerable time after being exposed to sunlight.

Many bodies have been found which shine‡ from two to eight seconds after removal from the sunlight into a dark room. Borax amongst salts, cotton and fine loaf-sugar amongst vegetable substances, egg-shells and shells of fish amongst animal substances, were found to possess this property in a considerable degree.

It was noted by Morgan (Phil. Trans. for 1785) that the more refrangible rays, or violet end of the spectrum, were most connected with phosphorescence.

Sir John Herschel observed that the violet end of the prismatic spectrum could be traced much farther when thrown upon a paper which was slightly tinged with turmeric. To the blue colour dispersed from a solution of disulphate of quinine, and similar cases, he gave the name of *epipolic* or *superficial* dispersion; but this name is not quite correct, for on examination it is found that the effect is that of an internal dispersion. This is well seen in a case discovered by Sir David Brewster; if we put green leaves of plants into alcohol, we obtain a tincture of chlorophyle, then allowing the beam of sunlight, condensed by a convex lens A in figure 97, to fall upon the solution, we see a bright red dispersed light from the conical beam as it passes through the liquid, which, though brightest near the surface of the liquid, is still not entirely superficial. Professor Stokes has more recently pursued the subject, and found many substances which possess this property in a high degree, which have enabled him to trace the fixed lines of the solar spectrum for the invisible chemical rays. Amongst these substances, the Canary glass or Uranium glass, which is very common in fancy glass work, has the property in a high degree. A piece of this glass placed in the prismatic solar spectrum in a dark room appears quite transparent in the red light, and opaque in the violet rays. Paper written upon with tincture of æsculine, prepared from horse-chestnut bark, exhibits the letters luminous in the violet and chemical light of the spectrum. An easy preparation to make is the following: bruise some seeds of the thorn-apple (*Datura stramonium*), and macerate them for some time in strong spirit of wine, rather more than will cover them. Paper written upon with this tincture shows very beautifully the phosphorescent writing in the violet and photographic, or chemical rays beyond the violet. They are well seen also in a dark chamber where only rays passing through blue glass are allowed to enter; the writing shining out brightly in the light which passes through such glass.

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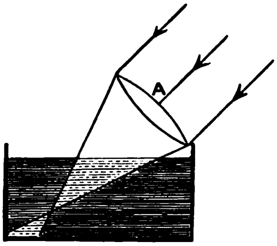
* 'Opticks,' pp. 107, 162, and 227.

† Phil. Trans. for 1768.

‡ 'De quamplurimis Phosphoris nunc primum detectis commentarius.' Auctore Jac. Barthol. Beccario. Bolognia, 1744. An account of the above, Phil. Trans. 1746.

Fig. 97.



The internal and superficial dispersion is shown strongly from an infusion of red sanders wood, which can be procured from the shops where dyeing drugs are sold. The wood in powder being infused in water for some time, we obtain a slightly coloured infusion, *which being taken from the wood,* and then a small quantity of liquid ammonia being added, it shows a brownish transmitted light, and a strong blue dispersed light.

### *Dichroism.*

In many double refracting bodies the two beams are differently coloured, and the effect is called dichroism*. Some cases have been discovered in which three and more colours are exhibited by the same body in different circumstances. These interesting and singular phenomena indicate molecular actions of the bodies upon light, of which we are not yet in a sufficiently advanced state of optical science to form any correct judgement; they are, however, only a part of a general property that some colours are reflected and dispersed, some absorbed and extinguished, whilst others are transmitted in a manner peculiar to each body.

### *Photometry.*

There is no property of light which requires more frequently to be considered in Physical Optics than intensity or brightness. The whole phenomena of interferences depend upon the different intensities exhibited in different parts of the interfering beams; and the light reflected and transmitted at the surfaces of bodies involves the quantity out of a given incident beam, which is subject to the one or the other of these effects. The rules for the intensities in some cases have been mentioned in previous pages, as Malus's rule for the intensities of double refracted beams, and the interference intensities in Newton's transmitted rings. The rules for the intensity generally involve mathematical expressions, which cannot be admitted into a popular treatise, but will be found in the second part of this work, which is devoted to a mathematical discussion of the subject.

Bouguer first appears successfully to have measured the intensities of the illumination in several cases, and in his work, '*Traité d'Optique,*' gives us numerous ingenious forms of photometers† adapted to different cases.

In some cases he examined the result experimentally with care, but was too prone to investigate rules from a few cases, and then to interpolate for intermediate cases. Amongst the cases on which he bestowed care was the reflexion of light at the surface of water at a very oblique incidence. The light falling at an inclination exceedingly small (or an incidence of nearly 90°) upon water, he found three-fourths of the incident light to be reflected. The light reflected by mercury he found to be about three-fourths of that incident.

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* See Brewster's 'Optics,' edition of 1853, p. 353.

† See also Priestley's 'History of Vision.'

Lambert in his 'Photometria' was still more inclined to generalization than Bouguer, and has added nothing important to the experimental foundation of the subject.

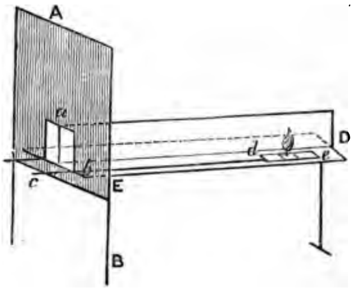
Count Rumford* paid some attention to photometry, but has added nothing important to Bouguer's results.

Sir William Herschel, in a paper in the Phil. Trans. for 1800, has left us the important result of the quantity of light reflected by the mirrors of his reflecting telescopes, as measured by a method given by Bouguer. He found that his excellent specula reflected at an incidence nearly perpendicular 67.262 rays out of every 100 rays incident upon them.

The author, in the year 1830, wishing to compare the polish of his specula, the making of which had been his favourite amusement in leisure hours for many years†, with those of Sir William Herschel, studied the method of best improving the photometer to adapt it to the purpose.

The annexed figure represents the form of the instrument found to be the best. An upright screen AB had an aperture in it, *ab*; this aperture was covered with the thin tissue paper used to take copies of written letters under the copying press. An upright piece of pasteboard CD, 50 inches long and 4 inches high, bisected the aperture *ab*, and was firmly fixed to a horizontal piece of wood along its middle; DE represents the half of this horizontal piece. On each side of the upright piece CD a sliding piece of

Fig. 98.



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* Phil. Trans. 1794.

† Brewster's Edinburgh Journal of Science for 1830, vol. iii. p. 278.

wood *de* carried a lamp, and the observations were made by judging of *the equality* of the illuminations upon the tissue paper from behind the screen AB, each half of *ab* being illuminated by its respective lamp. A long strip of wood *cd*, fastened to *de*, and passing through an opening in the screen, served to move backwards and forwards the lamps from behind AB, without need of taking the eye from the shade of the screen into the stronger light of the lamp, and thereby diminishing its sensitiveness. Divisions being marked on the strips, the distances of the lamps from *ab* can be read off by means of a dark lantern kept at hand for the purpose. The upright piece CD should be blackened on both sides, and on the side of which readings of the distances of the lamp require to be made, it should be covered with black cotton velvet as the darkest of all blacks.

Figure 99 represents the photometer as seen from above, the letters referring to the same parts as in fig. 98; also *f* and *g* show the small lamps, upon the slides attached to the graduated strips of wood.

Fig. 99.

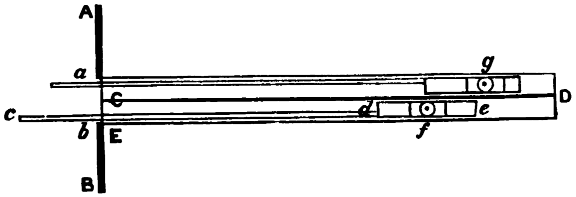
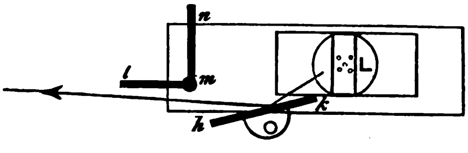


Figure 100 represents one of the slides with the small lamp L upon it. A mirror *hk* on a support attached to the slide may be put in such a position that the light from L may be reflected in the direction of the arrow to the screen at the desired incidence. The light direct from the lamp, or that which has been reflected by the mirror, may be allowed to shine upon the screen

Fig. 100.



successively by employing a rectangular blackened screen *lmn*, which, on being turned round 90°, shuts off the direct light, or the reflected light as required; and this is easily performed without bringing the eye into the strong lamp light by means of two threads from *l* and *n* carried to the screen AB.

The lamp *g* on the other side of the upright pasteboard is only for the purpose of comparison; thus, let the lamp *f* be at 40 inches from AB, and let the lamp *g* be moved until they give equal illuminations upon their respective halves of the tissue paper *ab*. This equality, with some practice, can be judged of with considerable accuracy when the eye looks upon the tissue paper behind the screen, and is kept out of the stronger light. The photometer must of course be used in a room without any other light than its own. The lamps being found to burn steadily, the screen *lmn* may be turned to cut off the direct light, and allow the reflected light to fall upon the screen. It will now be found that the illumination is much feebler than with the direct light, and the lamp and mirror must be drawn nearer in order to produce an equal illumination to that of the lamp *g*; let this distance be 34 inches, then since the illumination was the same in both cases, by the rule for photometry*, the light reflected was to the direct light as 34 squared to 40 squared, or the mirror reflected about 72 rays out of every 100 rays incident upon it. The light transmitted by plates of glass is easily determined by slight modifications of the slide *de*.

The greatest difficulty found by the author was to obtain lamps with small but bright flames, which would burn steadily for some time. He adopted shallow circular cups with a bridge across, having five holes, of which the middle one furnished air to the interior of the flames, which arose from four small wicks which passed through the other four holes, as marked at L (fig. 100).

The experiment may be now performed with much less labour, by using larger reflecting surfaces, and the candles which consume their wicks. The improved candles give a very uniform light, by taking care that the curve of the burning wick is always curved in the same direction in the photometer.

When the reflected light is feeble, as for instance that from glass at an incidence of 10°, 20°, or 30°, there is always a dispersed light from the parts about the lamp, however well blackened, which produces a light upon the tissue paper of considerable amount when the lamp is drawn near. This extraneous light must be determined and allowed for in order to have the true reflected light.

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* The author's treatise on Geometrical Optics, part 1. p. 12.

Using these methods, the light reflected by crown, plate, and flint-glass were found at the various incidences to be very nearly as in the table below; the actual quantities found are given in Brewster's Edinburgh Journal of Science for 1831, vol. iv. p. 53. The quantities in the table are calculated by a rule, which will be found in the second part of this work, and in the above-named paper.

*Table of the number of rays of light reflected out of* 100 *rays incident, by different kinds of glass at the* first *surface.*

| Angle of incidence. | Crown-glass, specific gravity 2.541. | Plate-glass, 2.511. | Flint-glass, 3.225. |
|---|---|---|---|
| 0° | 3.452 | 3.380 | 3.615 |
| 10 | 3.608 | 3.546 | 3.819 |
| 20 | 3.837 | 3.790 | 4.117 |
| 30 | 4.189 | 4.164 | 4.574 |
| 40 | 4.767 | 4.778 | 5.320 |
| 50 | 5.810 | 5.882 | 6.656 |
| 60 | 7.964 | 8.155 | 9.369 |
| 70 | 13.448 | 13.891 | 16.015 |
| 80 | 32.396 | 33.155 | 36.422 |
| 85 | 56.202 | 56.204 | 57.559 |
| 90 | 75.776 | 74.261 | 72.074 |

The light reflected by a highly polished metallic mirror is greatest at a perpendicular incidence, and contrary to the case of transparent bodies, it decreases as the incidence becomes more oblique.

A new and highly polished mirror of speculum metal, for the plane mirror of a Newtonian telescope, of which the author measured the reflective power, gave the following results:—

| Angle of incidence. | Rays reflected of 100 incident. |
|---|---|
| 20° | 69.45 |
| 40 | 66.79 |
| 60 | 64.91 |

These, with many other experiments, showed clearly that, contrary to the case of transparent bodies, the light reflected by highly polished metals is greatest at a perpendicular incidence. On investigating the law, the author found the above to be a part of the series in the following table:—

| Angle of incidence. | Rays reflected of 100 incident. |
|---|---|
| 0° | 72.3 |
| 10 | 70.85 |
| 20 | 69.43 |
| 30 | 68.11 |
| 40 | 66.91 |
| 50 | 65.87 |
| 60 | 65.03 |
| 70 | 64.41 |
| 80 | 64.04 |
| 90 | 63.91 |

A highly polished steel mirror gave the following results:—

| Angle of incidence. | Rays reflected of 100 incident. |
|---|---|
| 10° | 60.52 |
| 30 | 58.69 |
| 50 | 54.96 |

These show that the above law is not peculiar to speculum metal.

The results at the highest incidences being probably connected by some law applicable to all bodies, the author sought for the connexion in the specific heats of the substances taken for equal bulks, and found the following corroborative results:—

| Substance. | Specific gravity. | Refractive index. | Specific heats for equal bulks. | Reflexion at the highest incidence. |
|---|---|---|---|---|
| Flint-glass ...... | 3.225 | 1.570 | .43 | 72.07 |
| Plate-glass ...... | 2.511 | 1.517 | .39 | 74.26 |
| Crown-glass ... | 2.541 | 1.524 | .38 | 75.77 |
| Speculum metal | 8.9 | ...... | .67 | 63.91 |
| Steel (hard) ... | 7.8 | ...... | .88 | 53.60 |

which show that the light which a highly polished surface reflects at the highest incidence, is less as its specific heat is greater.

When the reflecting surfaces can be obtained of sufficient size, the preceding method of photometry would be employed, but there are many substances of which we may wish to know the reflective power which can never be obtained of sufficient size for that purpose. In these cases a comparison with the reflexion of glass will give us their reflective power by employing a *comparative photometer*.

By means of an instrument of this kind*, of which an improved form is given further on, it was found that diamond at 10° incidence reflected light the same in brightness, with crown-glass at 64° incidence nearly, or the diamond reflected 9.5 rays of every 100 incident, or nearly three times as much as glass. According to the undulatory theory, the number of reflected rays ought to have been twice as many nearly as they were found to be.

Selenite was found to reflect almost exactly the same as crown-glass; but mica, Iceland spar, rock-crystal, amethyst, and emerald reflected more, namely, 3.7 to 3.8 rays of every 100 incident, at an angle of incidence 5°.

By polishing glass of antimony† with fine prepared red oxide of iron on a polishing bed of soft pitch, the author got a flat piece of high polish which enabled him to compare its reflective power at a series of incidences with that of crown-glass. The experimental results differed but little from the following, calculated by the formula found for glass, but with the appropriate constants, as given by the experiments.

| Angle of incidence. | Glass of antimony reflects rays of 100 incident. |
|---|---|
| 0° | 8.20 |
| 10 | 8.36 |
| 20 | 8.60 |
| 30 | 8.98 |
| 40 | 9.59 |
| 50 | 10.68 |
| 60 | 12.93 |
| 70 | 18.52 |
| 80 | 36.65 |
| 85 | 57.07 |
| 90 | 72.20 |

---

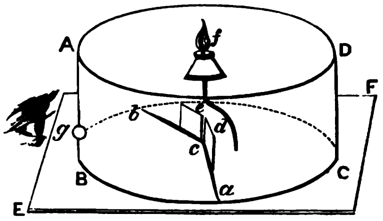
* Phil. Mag. for Sept. 1832.

† Ibid. for Jan. 1834.

The polarizing angle of glass of antimony was 65° nearly, which gives the refractive index 2.1 or 2.2, and the light reflected according to the undulatory theory should have been 13.33 rays of every 100 incident at a perpendicular incidence, whilst it was found to be only 8.2 rays by experiment.

To form a comparative photometer, take a square piece of wood EF (fig. 101), and finding its center *c*, make a circular groove around it. Take a rectangular piece of pasteboard about 4 inches broad, and bend it round into a cylindrical form ABCD, so that its lower edge may fit tightly into the groove. The upper part may be kept to the size and shape by a ring of wire, or other means. If a lamp, of which the flame is *f* in the figure, be fixed on a support, so that the flame is exactly in the axis of the cylinder, then every part of the cylindrical surface of the pasteboard will be equally illuminated. Let there be now a pivot in the center *c* of the groove, about which two arms *ca* and *cb* turn; and let them be made so as to carry the reflectors, which have to be compared, as for instance *cd* and *ce*. If we look through a hole in the pasteboard, as at *g*, we shall see the light coming from the reflectors *cd* and *ce* to be generally unequal. Suppose one of the reflectors *cd* to be crown-glass, blackened at its further surface, and *ce* some surface which reflects more at a perpendicular incidence than crown-glass does at that incidence, but less than crown-glass does at a high incidence.

Fig. 101.



Then when both are set to reflect to the eye the light coming from the parts of the pasteboard near *g*, that from *ce* will appear the brightest, but by inclining the other *cd*, we may bring the reflexion from it to equal that from *ce*. Now the angle of incidence upon each of the reflectors is easily got by having the inner edge of the circular groove graduated into degrees, and parts of degrees, for it equals half the arcs through which the arm *ca* or *cb* has been turned from the place where the reflexion of the eye-hole *g* was seen in the reflectors.

Hence knowing the intensity of the reflexion from crown-glass at any incidence, we find that for the other substance at a given incidence, since in the experiment they were brought to be equal.

The comparative photometer serves also to measure the relative intensities of the transmitted Newton's rings in homogeneous light; for making *cd* and *ce* both of the same crown-glass, and taking one to represent a dark ring, we can turn the other to a more oblique incidence until it represents the bright ring; and then knowing the reflexions from the glass, we have the relative intensities of the bright and dark rings. In this manner the author first determined the ratio of the intensities, as given in Chapter III., which he afterwards confirmed by another very different method, as there described.

Another experiment of considerable interest was the following:—one face of a thin rhombic plate of calc-spar being coated with black sealing-wax varnish, the reflexions of the opposite face were compared with the reflexion of crown-glass, and the results of the table were obtained when the planes of incidence were along the shorter and longer diagonals of the rhombic face.

| Angle of incidence. | Angle of incidence on crown-glass when the reflexions were equal. | |
|---|---|---|
| | For the plane of the shorter diagonal. | For the plane of the longer diagonal. |
| 5° | 22.0° | 21.7° |
| 10 | 25.4 | 25.1 |
| 57 | 61.6 | 59.1 |
| 57 | 61.7 | 59.8 |

These results are worthy of note, as showing that the intensity of the reflected light depends on other quantities besides the refractive index and angle of incidence, because the refractive index, as given by Brewster's law for the polarizing angle, was greater along the longer diagonal than along the shorter one.

There are many other phenomena often considered as belonging to Physical Optics, as well as details upon subjects which have been discussed, which are not noticed in this treatise. It has been the author's plan to present to the student the essential bases of the science, rather than to embarrass him with the minute details in many cases; but he trusts that the references given will suffice to indicate where these details in the different subjects will be met with, by those wishing to pursue the study of the science more completely.

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